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STOLAND FINAL REPORT

By John Grgurich
and Peter Bradbury

November 1976

Prepared under Contract No. NAS 2-6567 by
SPERRY FLIGHT SYSTEMS
Phoenix, Arizona

for

AMES RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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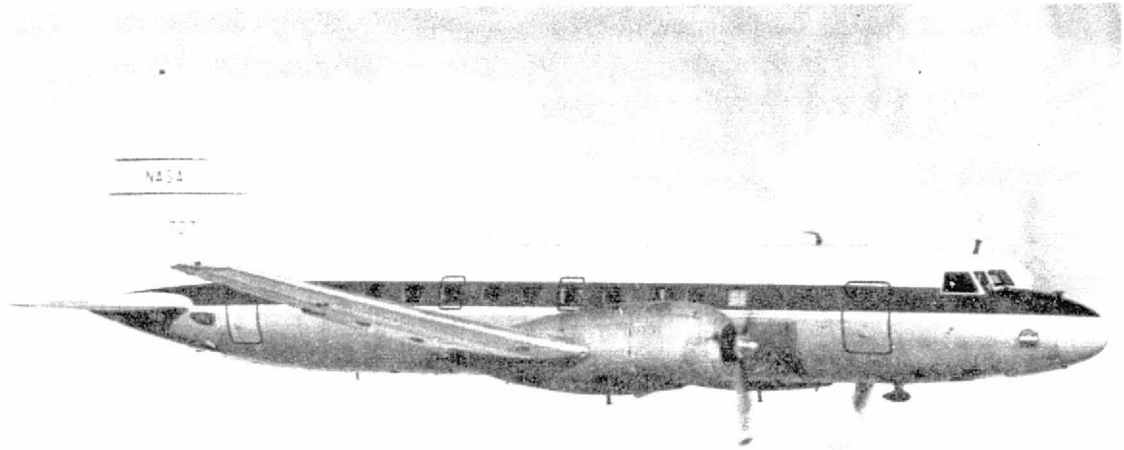
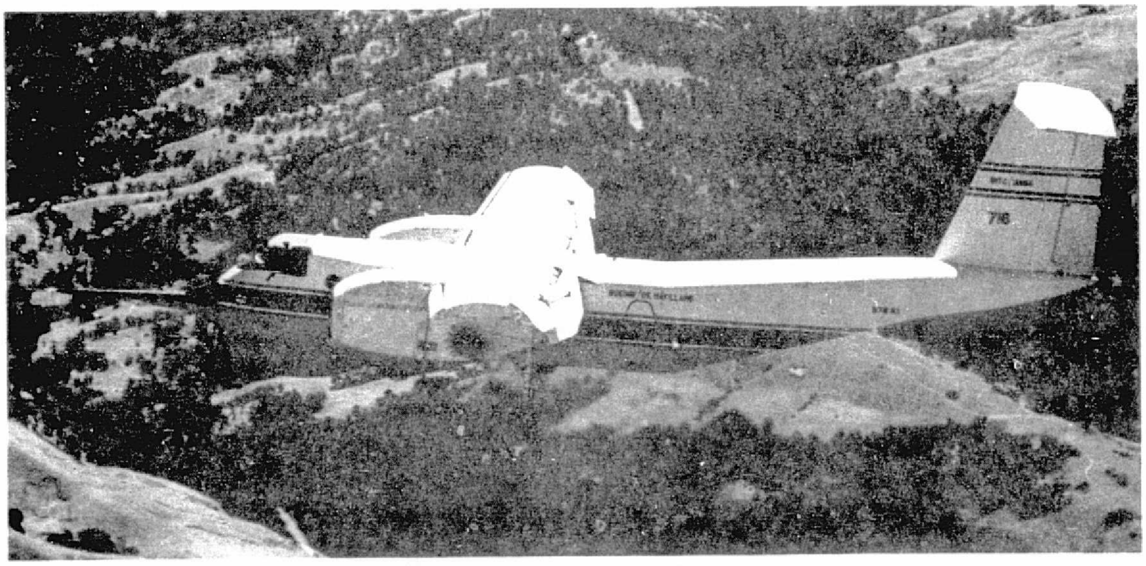


NASA CV-340 AIRCRAFT



AUGMENTOR WING JET STOL
RESEARCH AIRCRAFT

DHC-6 TWIN OTTER STOL AIRCRAFT

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SECTION I

SHORT HISTORY

A. INTRODUCTION

STOLAND is an integrated digital avionics system with electronic displays for performing navigation, guidance, automatic and flight director control on STOL research aircraft. STOLAND was designed and built by Sperry Flight Systems under Contract No. NAS2-6567 to provide NASA/Ames Research Center with a flexible avionics system for study of STOL navigation, guidance and control problems. The airborne system is presently installed both on the Augmentor Wing and the Twin Otter aircraft. The Augmentor Wing is a DeHavilland Buffalo fitted with jet engines, rotatable hot thrust nozzles, augmentor wings and a hydraulically powered elevator. Both of these aircraft are being used at NASA Ames for STOL research.

The STOLAND system includes air data, navigation, guidance, flight director (including a throttle flight director on the Augmentor Wing), 3-axis autopilot and autothrottle functions. The 3-axis autopilot and autothrottle control through parallel electric servos on both aircraft and on the Augmentor Wing the system also interfaces with three electrohydraulic series actuators which drive the roll control surfaces, elevator and rudder. The system incorporates automatic configuration control of the flaps and nozzles on the Augmentor Wing and of the flaps on the Twin Otter. Interfaces are also provided to control the wing flap chokes on the Augmentor Wing and the spoilers on the Twin Otter.

The STOLAND system has all the capabilities of a conventional integrated avionics system. Aircraft stabilization is provided in pitch, roll and yaw including control wheel steering in pitch and roll. The basic modes include altitude hold and select, indicated airspeed hold and select, flight path angle hold and select, and heading hold and select. The system can couple to TACAN and VOR/DME navaids for conventional radial flying. Approaches can be

made at Crows Landing using the MODILS (Modular Instrument Landing System). The MODILS provides solid angle airplane position information, so the glide-slope angle is not fixed by the ground installation. The desired glideslope angle can be selected by the pilot using the STOLAND Keyboard.

STOLAND provides terminal area navigation, guidance and control. The system will couple to and fly around a preselected four dimensional flight path to touchdown. The fourth dimension here refers to commanded speed control via the pilot or automatic control system to establish a fixed time of arrival at the touchdown point relatively independent of wind conditions. The flight path can be flown using the flight director or autopilot with or without autothrottle with the pilot making navaid selections and controlling the flaps and nozzles as required. A fully automatic mode (FULL AUTO) can be selected. In this mode the system automatically uses the most appropriate navaid. The aircraft is automatically configured for the approach and the system will complete a fully automatic flare, decrab maneuver and landing.

The STOLAND system stores the data for four different flight paths, all based on terminal area navigation at Crows Landing where TACAN and MODILS facilities are available. Any one can be selected by the pilot in flight. A plan view of the reference flight path is displayed on the Electronic Multi-function Display (MFD) together with a map showing salient features in the Crows Landing area. The airplane position is also displayed on the map. The map can be slewed up or down and left or right and its scale can be changed at the MFD Control Panel. The pilot can also select different map modes corresponding to north up, heading up or course up. Vertical information, waypoint and time data and navigation data are also presented on the MFD.

The Electronic Attitude Director Indicator (EADI) displays basic pitch and roll attitude and flight director commands. Several other displays are also included on the EADI. These include speed error, flight path angle, an approach window and a perspective runway. Numeric readouts of airspeed, radio altitude and vertical speed are also presented. The bezel of the EADI contains an approach progress display.

The Horizontal Situation Indicator (HSI) is a conventional, electromechanical instrument displaying magnetic heading, bearing, distance, horizontal deviation and vertical deviation.

Figure 1-1 is a block diagram of the STOLAND system. The heart of the system is the Sperry 1819A general purpose digital computer. The computer is a medium scale machine capable of solving real time problems in an aircraft environment. It can address 32K 18-bit words of memory. 16K of the memory is within the computer and the other 16K is housed in an Auxiliary Memory Unit. Input/output for the computer contains a fully buffered, parallel transfer, party line transmission system which communicates with the Data Adapter. The Data Adapter provides the required interface between the computer and the system sensors, motors and displays. It does all the necessary analog-to-digital, digital-to-analog and digital-to-digital conversions. The computer performs all the navigation, guidance and control computations in the system. It also does all the display computations except for pitch and roll attitude and radio altitude on the EADI and heading on the HSI. These four signals are interfaced directly from the vehicle sensors to the EADI and HSI and are not under computer control. This computer control of virtually the whole system makes STOLAND particularly suitable for experimental programs because navigation, guidance, control and display functions can be readily modified by changing the computer software program.

Pertinent digital data from the 1819A is recorded using the STOLAND Magnetic Tape Transport. The recorder can be turned on and off from the Status Panel. STOLAND also interfaces with a GFE Digital Data Acquisition System. This system records all pertinent analog and discrete data from STOLAND in addition to other airplane parameters. The recorded digital data can be readily changed because it is under 1819A software control.

A STOLAND simulation facility is in current use at NASA. This consists of a full 6-degree-of-freedom airplane simulation provided by NASA which interfaces with a Simulator STOLAND system supplied by Sperry. The facility permits full reference flight paths to be flown from a simulator cockpit and is used to validate flight software and hardware prior to flight test. It is also used for pilot training and familiarization.

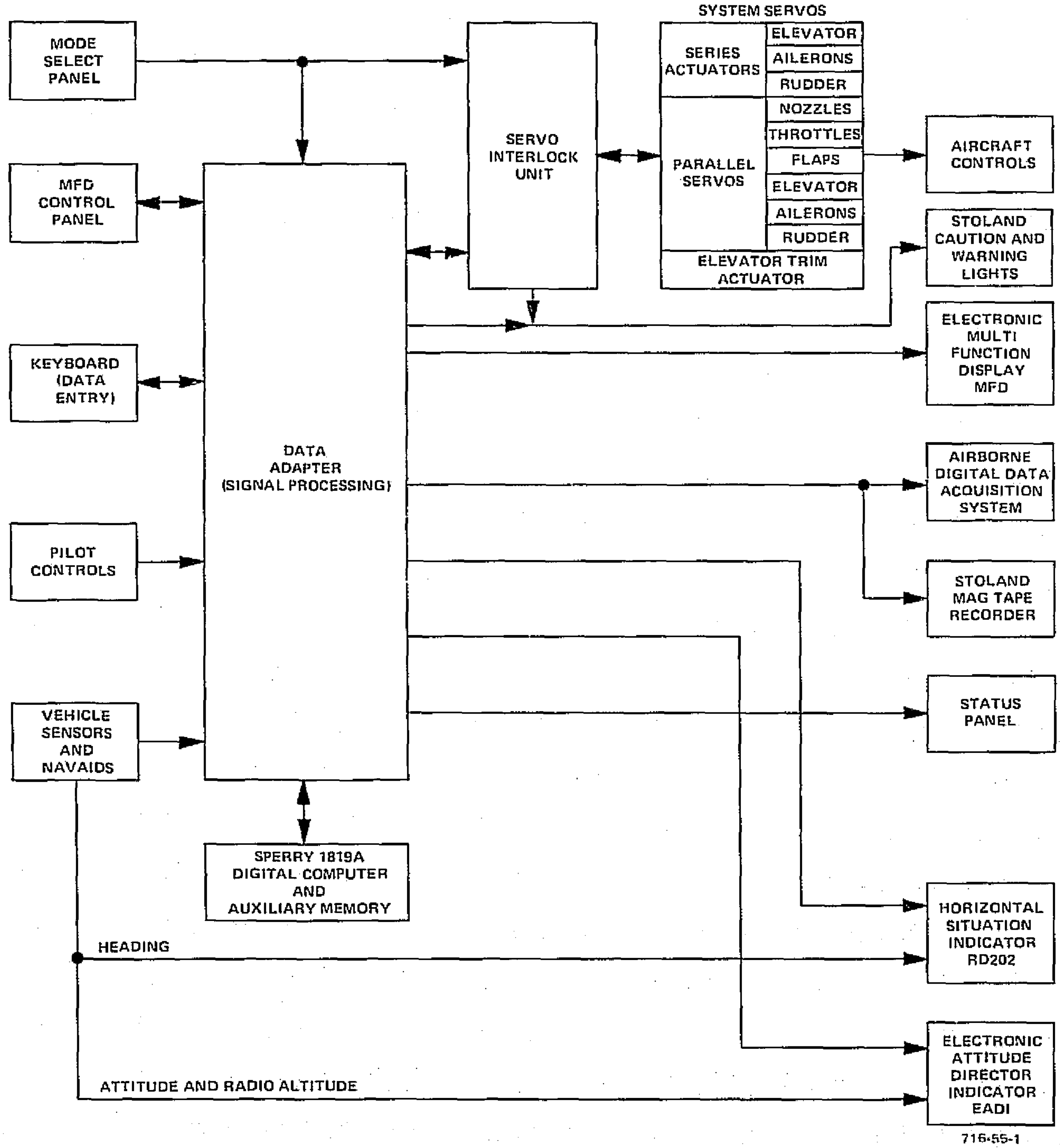

Figure 1-1
STOLAND Block Diagram

Data from the STOLAND magnetic tape can be rapidly reduced into strip chart recordings following each flight using specially developed software and the 1819A computer and Data Adapter portion of the Simulator STOLAND System.

B. STOLAND EQUIPMENT GENEALOGY

- The core elements of the STOLAND system which include the Digital Computer (1819A), Data Adapter, panels and pilot interactive controls and servo electronics units were applied to a NASA space shuttle flying simulator program in a CV-990 aircraft during 1971 and 1972. This was the first flight test application of the STOLAND core elements.

- All STOLAND flight hardware LRUs except the NAV receivers, air temperature probe and differential pressure transducers were designed and built by Sperry Flight Systems. This includes: sensors, displays, computer, electronics and servos.

- The 1819A airborne digital computer was designed and developed by Sperry Flight Systems in 1969 and 1970 for the SST Triplex, Fail-Operative Digital Autopilot (under Boeing/FAA contract).

- Elements of the Data Adapter unit were developed on the same contract.

- The 1819A was derived from an earlier machine, the 1819, designed by Univac in 1967 per Sperry Flight Systems specification. The 1819A expanded the repertoire, improved the I/O and memory subsystems, was redesigned with MSI and LSI technology and incorporated the physical and high-reliability design requirements of the SST program.

- The EADI and MFD display subsystems were selected for the SST but the designs were completed and prototypes built with Sperry funds.

C. BRIEF HISTORY OF THE STOLAND CONTRACT

The original contract was authorized on June 29, 1971 and required the delivery of a simulator STOLAND system and a flight STOLAND system for the Augmentor Wing.

Sperry completed the preliminary design of the system in November 1971. The final design review occurred in April 1972, and in August 1972 the complete set of simulator STOLAND equipment was delivered, installed and integrated with the NASA/Ames simulator cab and aircraft simulation facility. Simulator experiments and software and hardware validation has continued from this date.

A second set of flight equipment was ordered in August 1972. At that time, the plan was to put the first set of equipment on an unmodified Buffalo instead of the Augmentor Wing to gain experience on the less complicated Buffalo. The second set would go on the Augmentor Wing. Later, due to availability of aircraft, the first set of equipment was initially installed on a CV340 and the second set on the Augmentor Wing. Flight tests on the CV340 started first and flight testing on the Augmentor Wing commenced during the latter portion of the CV340 flight testing. The CV340 set was then removed from that aircraft and flight tested on a DeHavilland Twin Otter.

Static acceptance tests of the first flight system were conducted at Sperry in November 1972. This system was delivered in January 1973 and both the simulator system and the first flight system underwent extensive acceptance testing on the simulation facility in December 1972 and January 1973.

The first flight system was installed on the CV340 in March and April 1973. The installation did not include any autopilot or autothrottle servomotors but it enabled a full airborne environment checkout of the remaining system hardware and the software associated with air data, navigation, flight director and instrumentation. Flight testing on this aircraft continued until August 1973.

Testing of the second set of flight equipment started at Sperry in April 1973 with static acceptance tests. This set was delivered and then installed on the Augmentor Wing in mid 1973 following dynamic acceptance tests on the simulator. Initial shakedown flight tests on the Augmentor Wing were conducted in November and December 1973.

In 1974, extensive software work was completed by Sperry to develop 4D speed control for the Augmentor Wing. In addition, longitudinal control of the aircraft in the STOL configuration was changed to control the vertical flight path with thrust and the speed with elevator. At the same time, a throttle flight director was developed for use in the STOL configuration. Hardware additions were also made to allow STOLAND control of the wing flap chokes.

Flight tests on the Augmentor Wing were resumed in November 1974. The initial tests were of the wing flap choke interfaces. At this time, two sets of flight experiments were being conducted on the Augmentor Wing using STOLAND. The system was being used by NASA with a special set of research software in a STOL handling qualities research study. It was also being used with the Sperry-developed software and led to fully automatic 4D reference flight path guidance and control and automatic landings using the MODILS in the first quarter of 1975. NASA flight acceptance testing of Augmentor Wing STOLAND occurred in August 1975.

The first flight system was removed from the CV340 and installed on the Twin Otter by October 1975. Twin Otter flight testing started that month and led to NASA flight acceptance testing including fully automatic 4D reference flight path guidance and control and automatic landings in December 1975.

At the present time NASA is continuing their STOL research with the Augmentor Wing. This will include use of the wing flap chokes for direct lift control during approach and flare. The Twin Otter is having new wings fitted. These wings include spoilers for direct lift and improved roll control at low speeds. STOLAND is already configured to move the spoilers under computer software control.

SECTION II

HISTORY OF CONTRACTUAL CHANGES

The following table lists the significant STOLAND contract changes from the original contract (NAS 6567) which became effective on June 29, 1971 through to modification number 54 which became effective on February 21, 1975. The table is in chronological order and each change is identified by a modification number and a brief description of the change. It should be noted that the table refers only to hardware, software, documentation, and design studies and specifically does not cover changes associated with schedule shifts.

CONTRACT NAS2-6567

SIGNIFICANT CONTRACTUAL CHANGES

Modification Number	Effective Date	Description
Original	6/29/71	STOLAND Avionics System for the Augmentor Wing (AWJSRA) consisting of • Simulator STOLAND • Flight STOLAND
1.	7/28/71	• Aircraft application changed from Augmentor Wing to unmodified Buffalo (C-8A) • Pitch trim servo system added • GFE Navigation and Guidance Interface added
2.	8/27/71	• Airborne Hardware Simulator added to Simulator STOLAND
3.	9/1/71	• Slew switches added to the Mode Select Panels
4.	9/19/71	• Flight path angle acceleraton symbol added to the EADI

CONTRACT NAS2-6567

SIGNIFICANT CONTRACTUAL CHANGES (cont)

Modification Number	Effective Date	Description
7.	10/20/71	• Electromechanical HSI and amplifiers added • DDAS Instrumentation Unit added • EADI programmable display added • EADI TV mode interface added • Failure Mode Effects and Criticality Analysis (FMECA) deleted • Failure mode and reliability analysis added • Add interface for an RMI • Delete deliverable ground support equipment for STOLAND navaids
11.	1/17/72	• Control wheel and hub force sensor redesign • EADI flashing warning lights added • HSI bearing interface added • MFD baro altitude and real time displays added • VOR/ILS, DME, TACAN and Radio Altimeter navigation aids deleted and became GFE
12.	1/17/72	• Aircraft application changed from the Buffalo back to the Augmentor Wing
13.	2/8/72	• Feasibility study to examine using a STOLAND type of system for V/STOLAND
14.	2/22/72	• First increment of spares provisioning added
15.	3/2/72	• Added advance technology assessment to the V/STOLAND study
19.	5/2/72	• Card reader interface added to Simulator STOLAND • Servo Select Panel added to Flight STOLAND • Reference flight paths revised • Map selection procedure and map slew switch operation revised
22.	8/8/72	• Hardware fabrication for an additional set of equipment for the Augmentor Wing authorized

CONTRACT NAS 2-6567
SIGNIFICANT CONTRACTUAL CHANGES (cont)

Modification Number	Effective Date	Description
23.	8/8/72	• Buffalo propeller pitch dual clutch pack, servo and gearbox deleted • Flap detent and friction devices added to the Augmentor Wing and Buffalo sets • Servo mounting brackets for Augmentor Wing and Buffalo added • Added Buffalo and Augmentor Wing Accessory Boxes • Added servo installation checkout fixture • Added air data sensor mounting brackets for Buffalo and Augmentor Wing
25.	9/12/72	Second increment of spares provisioning added
26.	10/27/72	Third increment of spares provisioning added
27.	11/1/72	• Aircraft application change. The Buffalo system to go on a Convair CV340. Provided for CV340 installation and checkout
28.	11/15/72	• Modified Keyboard NUMBER/LETTER key • Refurbished Simulator STOLAND • GFE Tape Recorder for Augmentor Wing • Required environmental testing reduced • Provided a powered elevator interface and longitudinal SAS for the Augmentor Wing. • Changed the DDAS interface
29.	2/9/73	• Augmentor Wing flap quadrant detent redesigned to allow quick release
36.	6/20/73	• Added INS interface • Added elevator series actuator position indicator on the Augmentor Wing
39.	1/8/74	• Aircraft application change. The system on the CV340 was to be removed and installed with servos on the Twin Otter.

CONTRACT NAS2-6567
SIGNIFICANT CONTRACTUAL CHANGES (cont)

Modification Number	Effective Date	Description
39. (cont)		• Authorized and defined a Twin Otter study In this contract the Twin Otter and the Augmentor Wing subsequently became the final two aircraft to receive the two delivered STOLAND flight control systems.
40.	1/25/74	• Interface to the Augmentor Wing chokes added • Aircraft cable set for the Augmentor wing added
41.	2/12/74	• Environmental test requirements changed to include testing of all flight configured Control Wheel/Hub force transducers
42.	3/15/74	• Installation and flight test in the Twin Otter authorized
43.	4/25/74	• New pitch trim servo for the Twin Otter added • New dash number for the Twin Otter Servo Interlock Unit authorized • Software for the Task XI Handling Qualitites research added • Failure modes and effects analysis for the Twin Otter system added
44.	5/3/74	• Throttle flight director symbol added to the EADI
45.	5/17/74	• Software changes made to allow in-flight navigation at Moffett Field and between Moffett Field and Crows Landing. The previous system was specifically designed to navigate using the Crows Landing navaids only. • Extensive changes to the Augmentor Wing speed control software
47.	6/25/74	• STOL mode throttle flight director control laws implemented in the Augmentor Wing software using the new EADI symbol
52.	10/7/74	• Design of a STOLAND servo system in flight hardover tester added

Modification Number	Effective Date	Description
54.	2/21/75	• Experimental Spoiler Interface added to the Twin Otter system

SECTION III

TECHNICAL SUMMARY REPORT

A. OBJECTIVES

The Sperry objectives of the STOLAND program under contract NAS6567 are summarized below.

1. Design and fabricate a versatile, integrated digital avionics system capable of being installed in a variety of aircraft and/or simulators and used for navigation, guidance, control and display technology experiments.

2. Develop all hardware and software elements of this system and the necessary equipment and techniques required for system performance verification.

These objectives have been met as demonstrated by simulator dynamic acceptance tests and flight testing in three different aircraft - the CV340, the DeHavilland Twin Otter and the Augmentor Wing.

B. TECHNICAL DESCRIPTION OF STOLAND

The following description is intended to summarize the salient features of STOLAND. It is by no means complete. For a more detailed description the reader should refer to the STOLAND System Operation and Maintenance Manuals which give a good overview from the pilot operating standpoint (References 1 and 2). Further technical details will of course be found in the hardware and software documentation of the system (References 3 and 4).

1. Computer Functions

The Sperry 1819A general purpose airborne digital computer is a 1970 vintage MSI TTL machine. It has 16K of magnetic core memory and an additional 16K in an auxiliary memory unit. As will be shown later, only a part of this memory is needed to perform all of the functions listed and discussed below. The remainder is available for NASA flight experiments.

- 5-Axis Closed Loop Stabilization and Control .... Manual and Automatic
- 4-D Guidance and Navigation .... Straight and Helical Paths
- Autoland
- Area Navigation .... VOR, TACAN, Microwave Scanning Beams, Air Data, Inertial Smoothing
- Strapdown Inertial Navigation .... Short term
- Moving Map Display .... Trend vector prediction, landmark symbology, flight path waypoint data, etc
- EADI with landing runway perspective and 3-axis flight director
- Air Data Computation .... From raw data barometric sensors
- Autopilot and system monitoring
- Preflight Checkout

Five axes of closed loop control involve the computations required to operate elevator, elevator trim, aileron and rudder servos, an autothrottle servo, engine nozzle servo (Augmentor Wing STOL aircraft) for variable thrust deflection and a flap servo for automatic flap deployment. The elevator, throttle, nozzle and flap servos are operated in response to decoupling control laws which control speed, flight path angle and angle of attack as the aircraft is constrained by the 4-D guidance equations to follow straight and helical paths through a sequence of programmable waypoints, terminating in an automatic landing.

Position and velocity state estimation of the aircraft is computed from VOR, DME, TACAN, microwave scanning beam ILS (MODILS), air data, aircraft Euler angles (obtained from conventional attitude and heading reference systems), and body axis accelerometers. The strapdown inertial velocity computations obtained from the accelerometers and the appropriate transformation equations serve to smooth the position and velocity determinations computed from the radio navigation receivers and air data measurements.

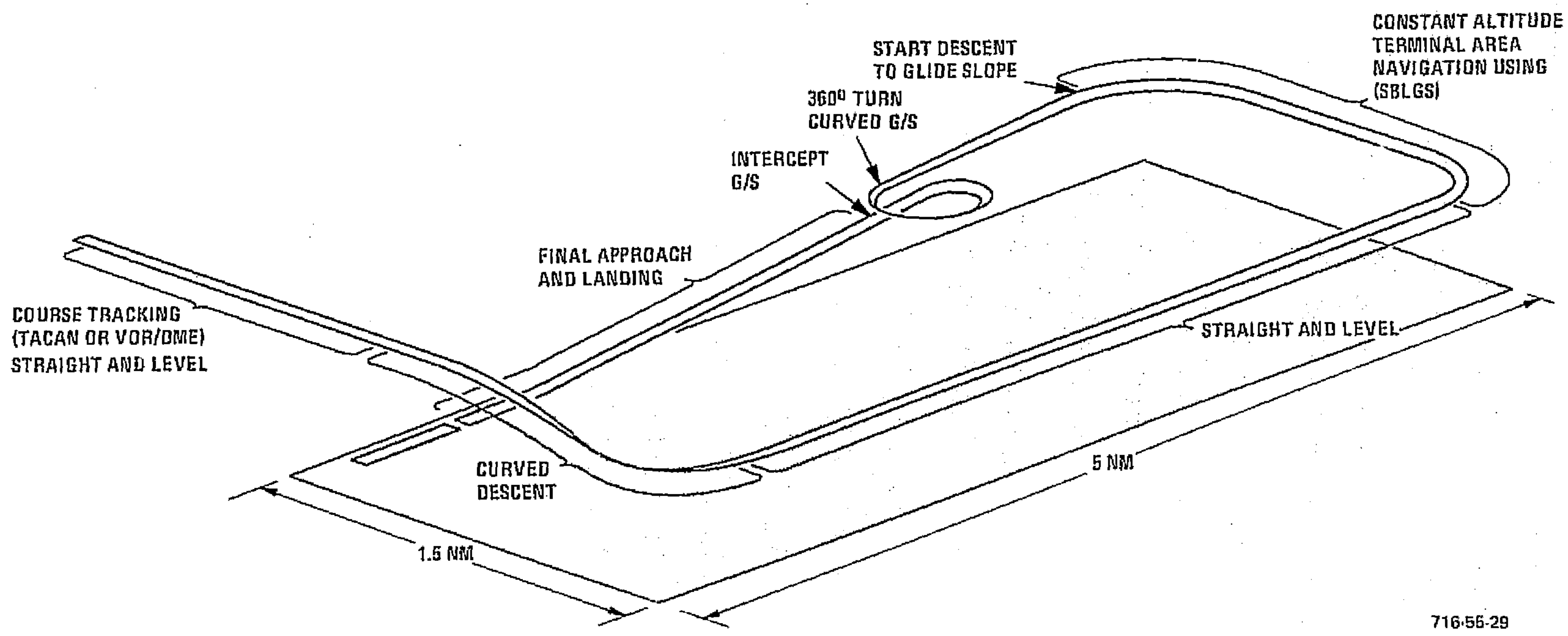

Figure 3-1
Typical Reference Flight Path Trajectory

The position and velocity state estimations obtained from the navigation algorithms, in conjunction with stored data on air navigation routes, landmarks and selected waypoints contribute to the generation of a moving map display. The map includes a trend vector (predicted future position in 10-second intervals), record of previous track, the desired flight path (interconnected waypoints), azimuth scale and tabulations of aircraft status in alphanumeric format.

The Electronic Attitude Director (EADI) displays three flight director pointers, digital readouts of airspeed and vertical speed, a flight path angle and flight path acceleration cue, drift angle, a lateral and vertical flight path error window and a perspective runway, all under computer software control.

The air data computation of altitude, calibrated airspeed, true airspeed, and total air temperature is performed by the computer from raw sensor inputs (static pressure, total pressure, total air temperature).

Autopilot and servo system monitoring to detect equipment failures and to activate safe system shutdown controls is performed by the digital computer. The airborne computer also includes a self-contained central integrated preflight test program which exercises the entire complement of avionics equipment, records failures and displays diagnostic messages that provide fault isolation to the specific malfunctioned LRU or device.

2. Typical Reference Flight Path Trajectory

Figure 3-1 illustrates a typical terminal area trajectory which was used as a reference path to test the navigation, guidance and control accuracy of the STOLAND avionics system. The desired flight path is defined by a sequence of waypoints and curvature radii. Each waypoint is specified by three position coordinates and nominal, maximum and minimum airspeeds. The local coordinate frame is centered on the runway aimpoint. A final time constrained waypoint is defined at the landing gate on the final approach glide path.

In the trajectory illustrated, a transition to STOL speeds (from about 120 knots to 65 knots) starts during the turn to the runway heading as the aircraft starts its glideslope descent. A final 360-degree helical glideslope appears prior to capture of the final approach glide path. While these trajectories may not be representative of practical operating procedures in the ATC environment, they provide a severe test for navigation, guidance and control accuracies. Navigation capability is enhanced by the availability of the precision DME plus azimuth and elevation scanning beams of the MLS system being evaluated.

3. Terminal Area Flight Path

Figure 3-2 is a plan view of the previously illustrated reference flight path with a simulation run of the navigation system's characteristics superimposed. In the region where the navigation algorithm's position estimate is primarily dependent upon TACAN, the errors approach a maximum of 2000 feet. When the aircraft reaches the region where the MLS (MODILS) is valid, the errors converge to non-perceptible magnitudes on the scale illustrated. The inertial filtering smooths the estimated reference path as shown by the dashed line.

4. Cockpit Displays During Reference Flight Path Control (Start of Deceleration)

Figure 3-3 illustrates the cockpit displays when the aircraft is being controlled by the STOLAND system to fly the reference trajectory discussed previously. The aircraft has started its deceleration phase on the turn to align with the runway heading. The moving map display (in the Heading-Up mode) shows the aircraft symbol passing waypoint 10 and on the curved path toward waypoint 11. The status display on the map or Multi-Function Display (MFD) reads WPT (waypoint) 11 as the next waypoint, CALT (commanded altitude of waypoint 11) at 3000 feet, TWPT (time to next waypoint) at 31 seconds, Δ T (the instantaneous time error for the 4-D guidance) at zero and PTE (predicted time error at the terminal waypoint) at zero. The EADI shows the aircraft well within the software-controlled guidance window, although it is 20 feet high as indicated by the actual altitude in the upper left corner (3020 feet) and the commanded altitude (3000 feet). The vertical speed is -200 feet per minute (upper center) correcting for this error, and

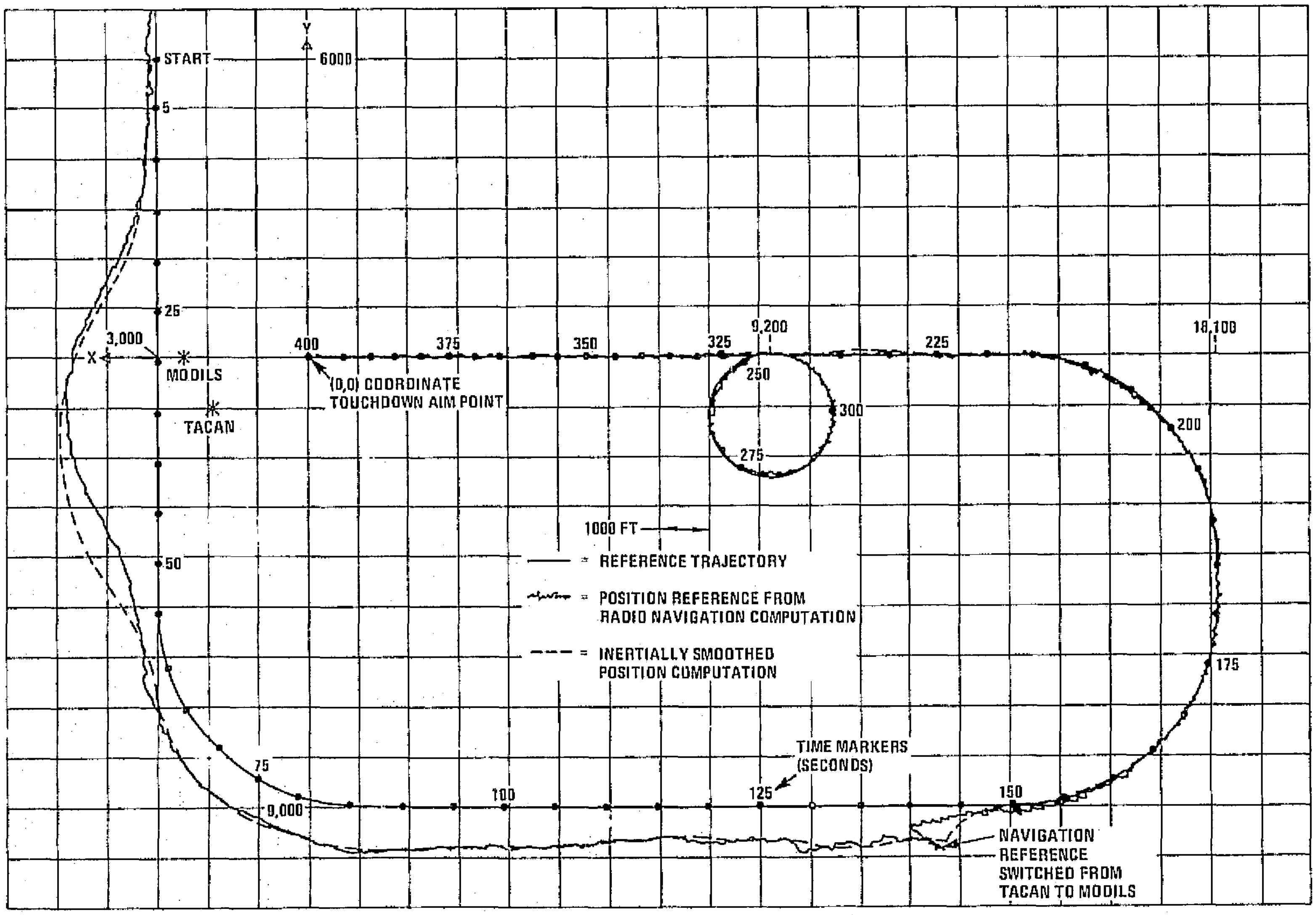

Figure 3-2
Terminal Area Flight Path

the airspeed is 95 knots (upper left). The electromechanical HSI under the EADI is completely under software control, indicating path deviation, course, distance to next waypoint, etc.

This photograph was taken at the Sperry STOLAND validation facility where all of the airborne equipment was operating and controlling a 6-degree-of-freedom simulation of the aircraft. The following displays, some of which were developed after this photograph was taken, are not shown in the picture.

On the EADI, radio altitude is not shown because the aircraft is more than 2500 feet above the ground. The pitch and roll flight director and the throttle flight director are not shown because FLT DIR is not engaged at the Mode Select Panel. The EADI speed error display is not shown.

On the MFD, PTE has been replaced by two symbols OT and ET. OT is the original time of arrival at the final waypoint. ET is also the time of arrival at the final waypoint if the aircraft is on schedule or capable of making up schedule. If the computer estimates that schedule cannot be made up (due to excessive wind changes or airspeed safety contraints) ET will differ from OT and show the latest estimated time of arrival.

The top left hand corner of the MFD now includes a navigation aid annunciation display. This display identifies by type (VOR, TAC, MODILS) and station mnemonic which navaid is currently being used by STOLAND. It also indicates the validity of the raw data signals from the relevant navigation equipment.

5. Cockpit Displays on Final Approach (About 3 Seconds Prior to Flareout)

Figure 3-4 is a view of the cockpit displays about 3 minutes after the previous illustration. The aircraft is now 80 feet above the runway (EADI - upper right radio altitude window). On the MFD the aircraft is seen at about waypoint 17, the 100-foot threshold, and approaching waypoint 18, the runway aimpoint. The map now displays the Crows Landing runway, the STOLAND test site. Also shown is the air navigation symbology (VOR/DME station, etc) which was absent in the previous illustration. The selection

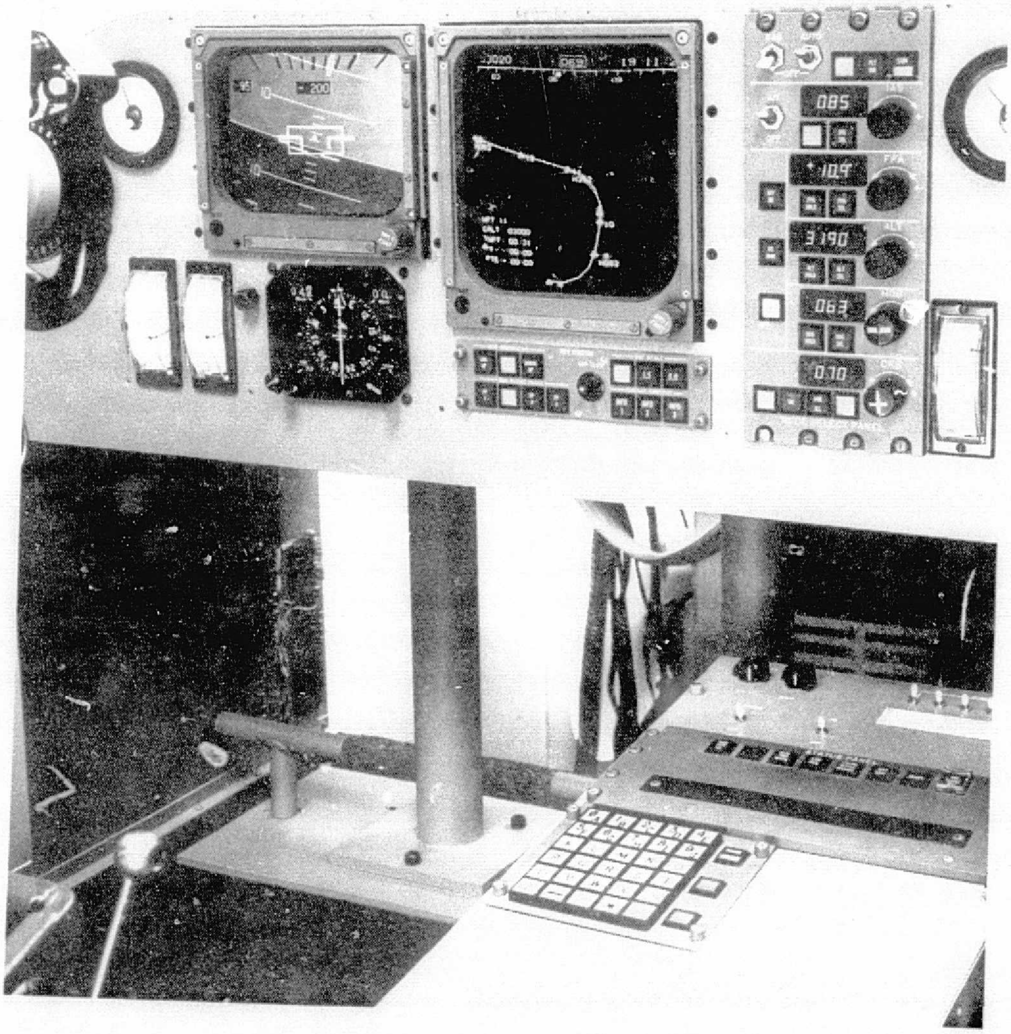

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Figure 3-3
Cockpit Displays During Reference Flight Path Control
(Start of Deceleration)

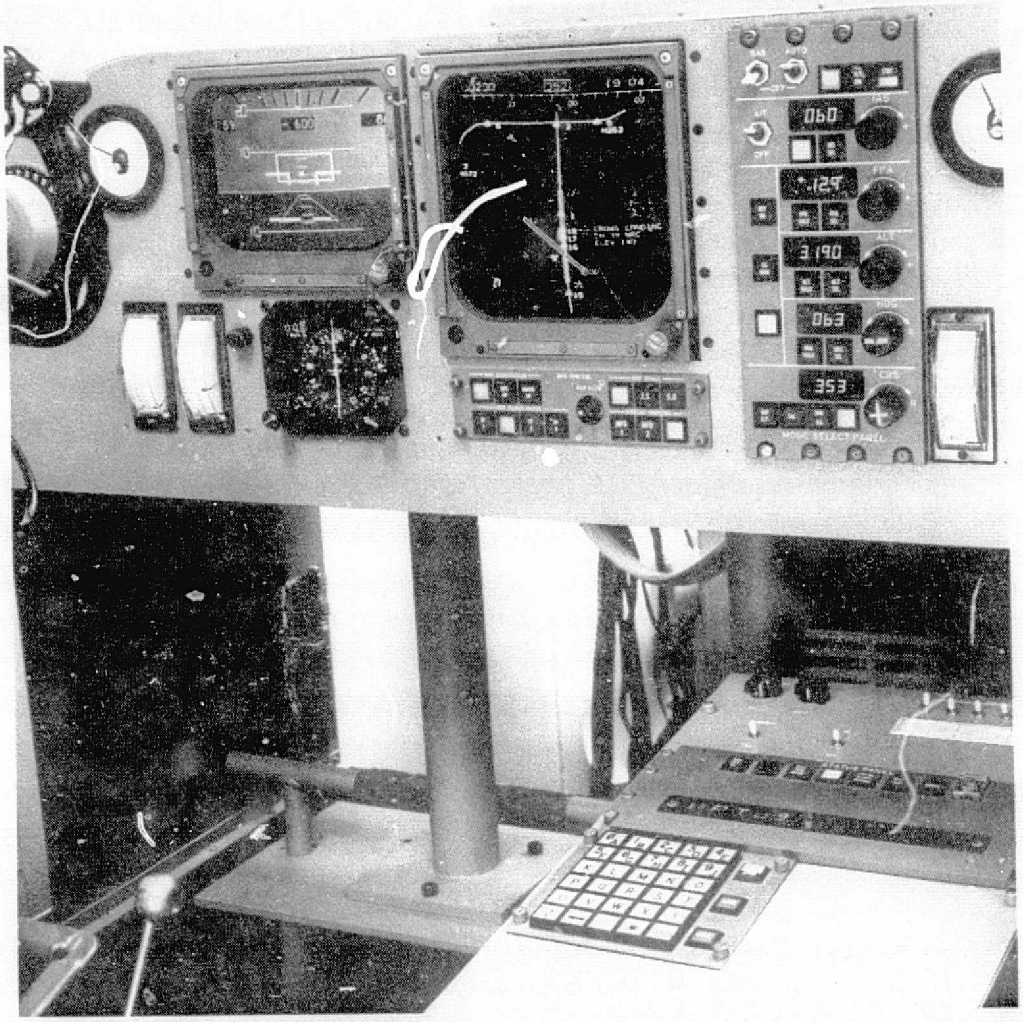

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Figure 3-4
Cockpit Displays During Reference Flight Path Control
(About 3 Seconds Prior to Flareout)

of symbology is obtained through the MFD controller display content pushbuttons. These serve as a simple means of editing the moving map display to eliminate a tendency to clutter. In the fixed map, moving aircraft mode (NORTH-UP), the clutter problem is minimized. The software provides a considerable amount of editing such as cutting the picture to fit the viewing area, etc, but a complete editing program to ensure no overlapping of information and the incorporation of all necessary priorities has been estimated to require about 4K to 8K of additional memory.

Note that the perspective runway is now seen on the EADI. The horizontal bar at the front of the runway is the flight path angle (velocity vector) symbol and the bar to the left is the flight path acceleration symbol. The airspeed is 59 knots, the vertical speed is -600 feet per minute and the aircraft is on a -7.5 degree glide path at a 4.0 degree angle-of-attack (all information shown on the EADI).

The displays not shown in the previous illustration are also missing on this photograph, except for radio altitude.

6. <u>4-D Guidance Concept</u>

In previous discussions it was seen that the STOLAND system computes guidance laws which maneuver the aircraft to acquire and track the flight path defined by the interconnection of the specified sequence of waypoints. These guidance equations involve constraining the aircraft in three spatial dimensions defined by instantaneous x, y and z coordinates with respect to a coordinate frame centered at the runway aimpoint. The STOLAND program is also concerned with the fourth dimension or time constraints which must be imposed on the aircraft trajectory for ATC compatibility. Although it appears that the most practical method of achieving specified time constraints at critical waypoints would involve path stretching and contracting, the STOLAND ground rule was to implement a fixed path 4-D guidance system. Subsequent STOLAND flight experiments will consider many other 4-D guidance concepts - a capability provided by STOLAND's flexible software modularity.

Figure 3-5 shows the fixed path, 4-D guidance concept which was incorporated into the basic STOLAND software. This concept is extremely versatile because the phantom aircraft's position may be defined by any desired algorithm and is completely uncoupled from the speed control algorithms which are used to chase the target. Thus each type of aircraft has its own optimized set of speed control laws which may involve blended combinations of throttle, thrust vector, flaps, and elevator modulations. These speed control laws are used to achieve a speed change which in the 4-D guidance concept is proportional to the position error between aircraft and target. The phantom target flies at nominal speeds and reaches the time constrained waypoint j having coordinates (x_j, y_j, Z_j, T_j) at the specified time T_j.

7. Definition of Phantom Trajectory

If we constrain the phantom target to fly precisely on the 3-D trajectory at a defined nominal airspeed, V_{AN}, and if we can accurately estimate the wind velocity vector, V_W, we can then define the phantom's ground velocity, V_{GN}, at every point on the trajectory. If we know ground speed at every point, we know the time required for the target aircraft to move from one waypoint to the next. This computation procedure is used to generate an array of target times for each waypoint. This array is recomputed every 10 seconds on the basis of more recent wind estimates. Obviously the accuracy and validity of this concept is dependent upon the assumption that the most recent wind estimate will be relatively unchanged as the flight proceeds. Wind estimates are obtained from the vector subtraction of airspeed (derived from the air data computations) and ground speed (derived from the radio-inertial navigation algorithms).

The computations required for the phantom trajectory are summarized below. Assume the final time critical or inviolate waypoint is j. Assume that the phantom flies at the nominal airspeed V_{AN} between points (j-1) and j. Now the time Δt_{j-1} required to fly the distance D_{j-1} between (j-1) and j using the latest wind estimate to compute the nominal ground speed V_{GN} may be determined.

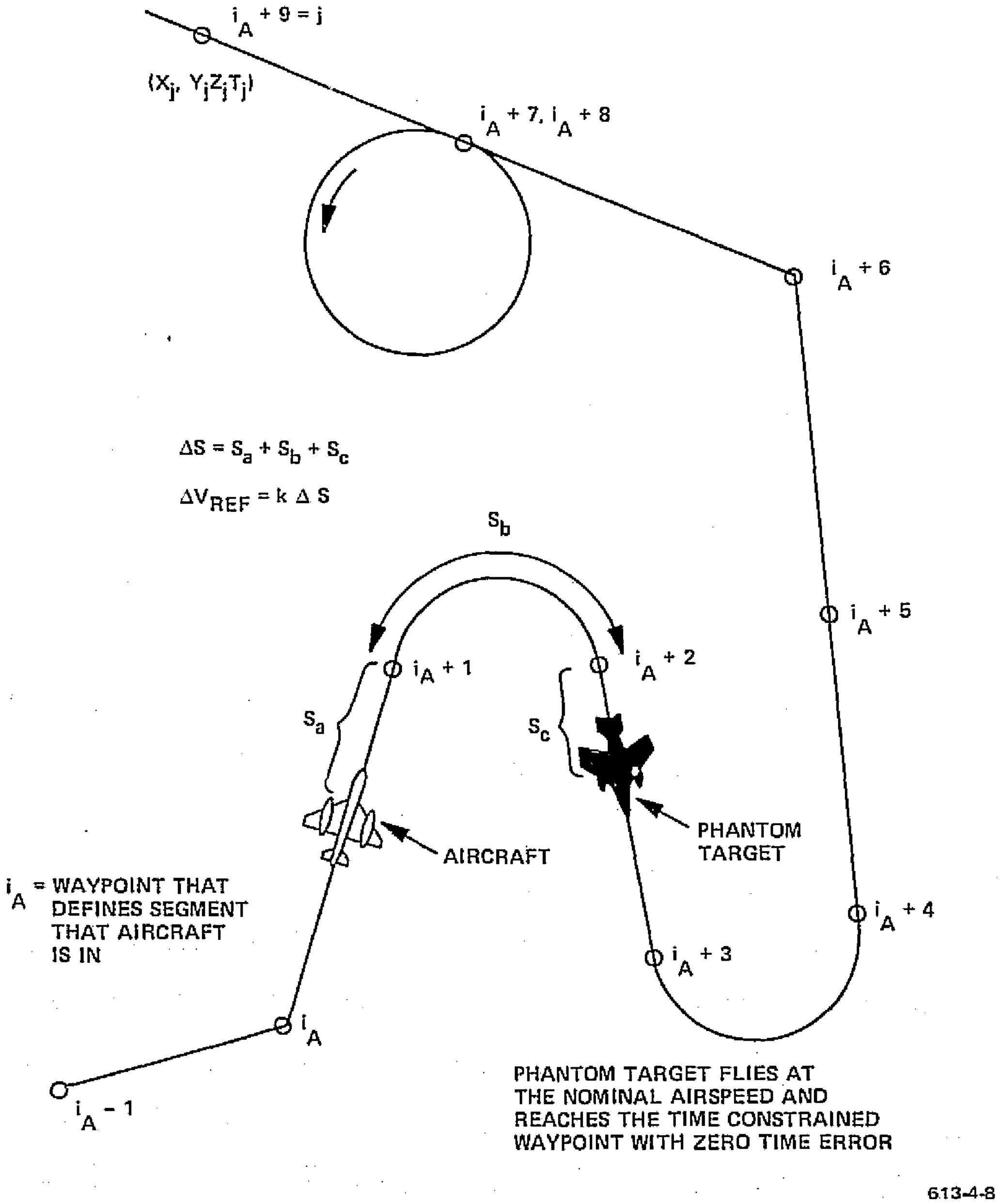

Figure 3-5
4-D Guidance Concept

$$V_{GN} = \overline{V}_{AN} + \overline{V}_W$$

$$\Delta t_{j-1} = \int_0^{D_{j-1}} \frac{d(S_{j-1})}{V_{GN}(S_{j-1})}$$

From this integral, the time $t_{(j-1)}$ that the phantom arrives at point j-1 is $t_j - \Delta t_{j-1}$. This process is repeated for all waypoints moving backwards from the time-constrained waypoint using the appropriate integration rules depending on both geometry and nominal velocity gradients. The process yields a sequence of target times $[t_{i_T}]$ which represent the times at which the phantom target reaches waypoint i.

The phantom trajectory is propagated from each waypoint i starting at t_{i_T} when the phantom is over that waypoint. The distance of the phantom target along the segment i following waypoint i is:

$$S_{i,T}(t) = \int_{t_{iT}}^{t} V_{GN}\, S_{i,T}(t')\, dt'$$

V_{GN} the ground speed integrand is a function of position along the trajectory which is in turn a function of time t'.

Various simplifications are made to evaluate this integral equation.

Winds are re-estimated every 10 seconds so that the $[t_{i,T}]$ sequence of times is recomputed every 10 seconds and $S_{i,T}(t)$ is redefined by the new wind estimates.

8. Simplified Flow of STOLAND Computations

Figure 3-6 is a simplified representation of the computation flow of the STOLAND system. It provides an overview of the interrelationships between the main functional categories, which are:

- Navigation - including state estimation filtering which blends optimum combinations of radio, inertial and air data measurements to define the aircraft velocity and position vectors.
- Air Data Computation
- Guidance - Steering equations to maneuver the aircraft to the specified flight path and flight path generation from waypoint arrays and pilot-selected reference parameters.
- Control - Attitude stabilization, control stick steering or control augmentation, speed and configuration control (throttles, flaps, nozzles), turn coordination, maneuver constraints, control of nine servo channels. (Includes flight director computations.)
- Displays - EADI three-axis flight director, perspective runway, digital readouts of speed, rate of climb, etc; MFD (moving or fixed map with slew controls, selected scale and various modes); alphanumeric display panels for pilot interactive controls with warning and status messages.
- System Monitoring - In-flight fault detection and fail-safe engage/shutdown controls
- Central integrated test and automated maintenance management that exercises all equipment during preflight test, fault isolates and reports failures with alphanumeric messages and stored maintenance data

9. Flight STOLAND Equipment Complement

The STOLAND LRUs are categorized and listed in Table 3-1. All this equipment, except the navigation sensors and the heading reference system, was supplied by Sperry under the STOLAND contract.

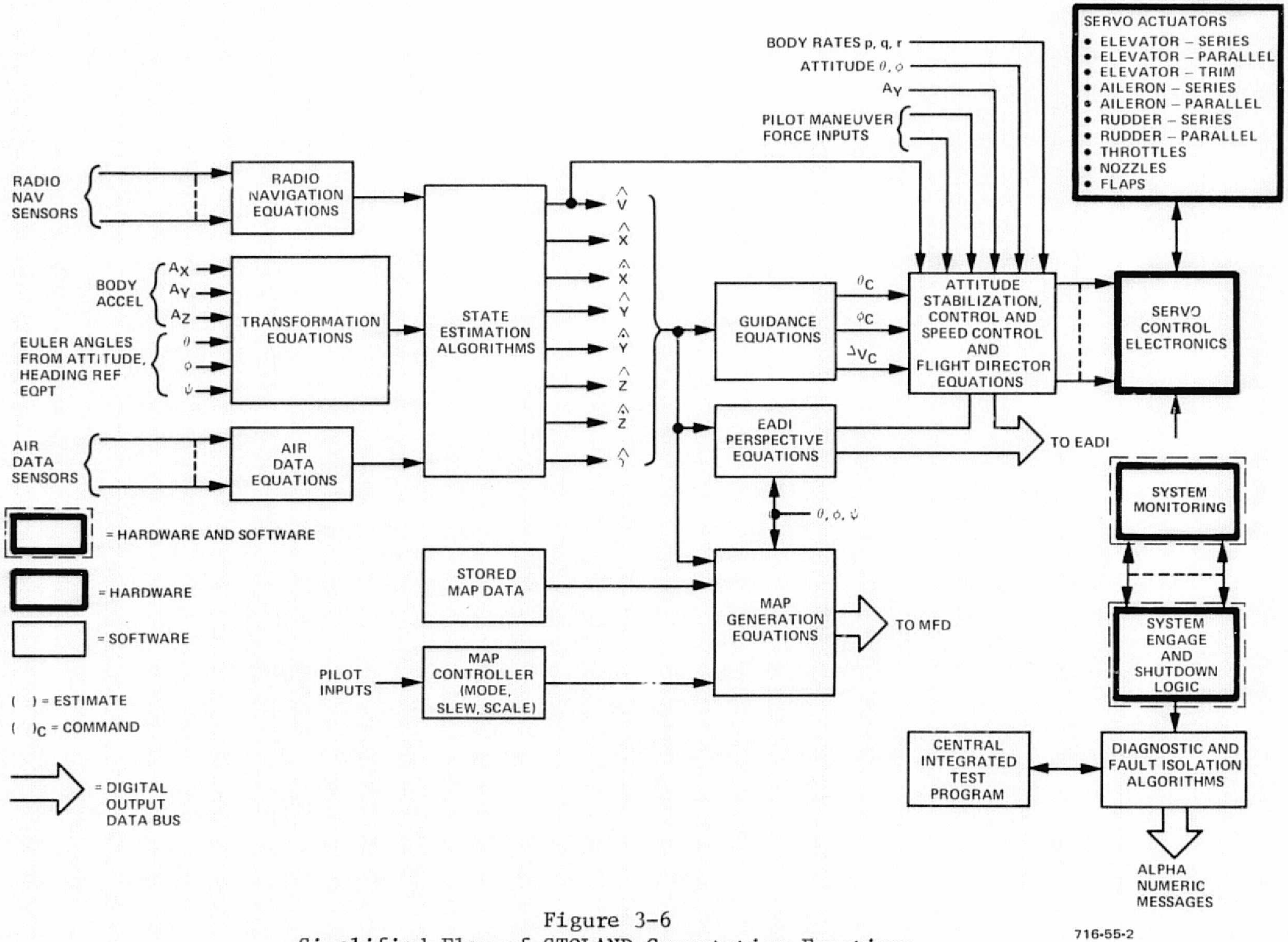

Figure 3-6
Simplified Flow of STOLAND Computation Functions

TABLE 3-1

FLIGHT STOLAND EQUIPMENT COMPLEMENT

- Computer Complex
  - 1819A Digital Computer
  - 1919A Auxiliary Memory Unit
  - Data Adapter
  - Magnetic Tape Transport
- Cockpit Units and Associated Electronics
  - EADI Display Unit and Symbol Generator
  - MFD Display Unit and Symbol Generator
  - Mode Select Panel
  - Status Panel
  - Keyboard
  - Panel Power Supply
  - RD-200 and Instrument Amplifier Rack
  - Control Wheel and Hub Force Sensor
  - HSI Signal Conditioning Unit
- Air Data Sensors
  - Total Temperature Probe
  - Static Pressure Transducer
  - Differential Pressure Transducer (Airspeed)
- Stabilization and Control Sensors
  - Vertical Gyro
  - Heading Reference System
  - Rate Gyro Assembly
  - Accelerometer Assembly
  - Flap Position Transducer
  - Column and Wheel Hub Force Transducer Assembly
- Servos and Associated Equipment
  - Pitch, Roll, Flap and Rudder Surface Servos
  - Autothrottle Servo, Dual Clutch Pack and Gearbox
  - Nozzle Servo, Dual Clutch Pack and Gearbox
  - Servo Interlock Unit
  - Elevator Trim Servo

TABLE 3-1 (cont)

FLIGHT STOLAND EQUIPMENT COMPLEMENT

- DDAS Instrumentation Unit

- Navigation Sensors
  - VHF NAV Receiver (VOR, ILS .... Glideslope, Localizer)
  - DME
  - VHF NAV Controller
  - TACAN Receiver/Transmitter
  - TACAN Controller
  - Radio Altimeter
  - SBLGS (MODILS .... MLS Scanning Beams)
  - INS (Optional)

The functions and interrelationships of this equipment will be described later under system architecture. For the most part, the basic function of each device can be easily deduced from its name and the category under which it is listed. The following units require additional explanation.

In the Computer Complex, the Magnetic Tape Transport is used to load the computer program and to record inflight data.

Under Cockpit Units and Associated Electronics, the Panel Power Supply is a special power conditioning unit that supplies the cockpit panels. The RD-200 is a conventional HSI that has been modified to permit 1819A computer control of all its indications except heading. This computer control includes the selected heading, selected course, all warning flags, the vertical and horizontal deviations, the two distance displays and the to-from indicator. The HSI Signal Conditioning Unit is a special electronic assembly required to implement the digital-to-synchro conversions for interfacing with the RD-200 and its standard Instrument Amplifier Rack.

Under Servos and Associated Equipment, the Servo Interlock Unit contains the servo drive electronics for the system servos and actuators. It also contains the engage circuitry for these devices and some of the servo monitoring. In addition to the servos listed, the Servo Interlock Unit also

controls the drive of three electrohydraulic series actuators in pitch, roll and yaw and the wing flap chokes on the Augmentor Wing. Provision is also provided for drive of the spoilers on the Spoiler Wing Twin Otter.

The DDAS Instrumentation Unit is a special signal conditioning LRU that processes miscellaneous analog signals for transmission to the aircraft's Digital Data Acquisition System (DDAS). In addition to these analog signals, all pertinent data from the 1819A computer is also transmitted to the DDAS directly on a fast parallel data transfer interface via the Data Adapter.

Under Navigation Sensors, provision is included for interfacing to an ARINC 561 type INS. This permits flight experiments to determine the navigation and guidance improvement attainable with an INS rather than the simpler strapdown inertial element used in the present STOLAND system.

10. STOLAND Flight Equipment Rack

The STOLAND equipment, except for cockpit displays, controls, servos and the inertial sensors, is installed and integrated within the removable pallet shown in Figure 3-7. The back of this pallet contains connectors for all incoming and outgoing cables and terminal blocks for testing. The pallet contains its own cooling air supply and appropriate air flow distribution and monitoring instrumentation.

At the upper left corner, provision is included for installing a Status Panel and Keyboard to permit test engineers to remotely control STOLAND data and experiments from the rear of the aircraft (if desired).

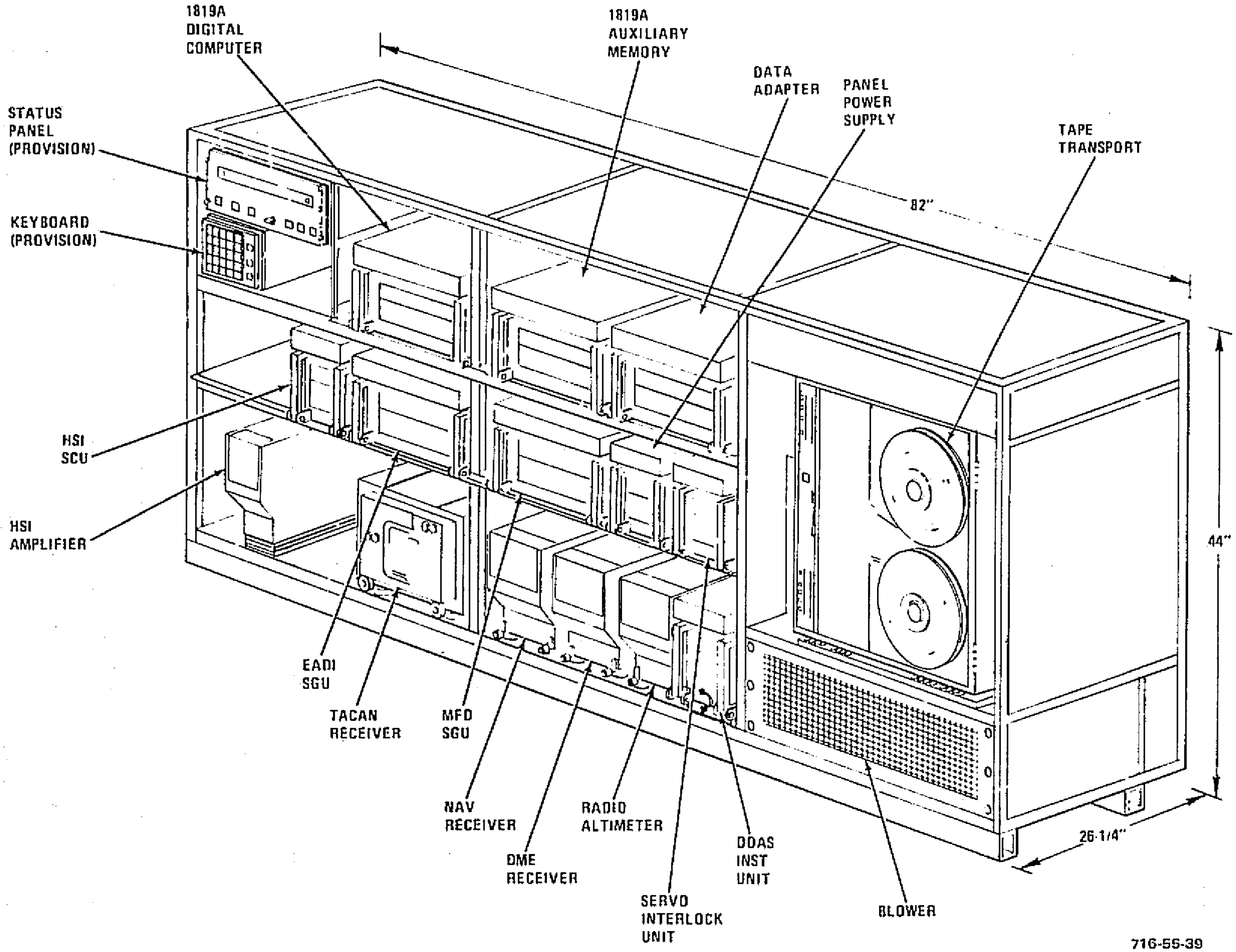

Figure 3-7
STOLAND Flight Equipment Rack

11. Photographs of STOLAND Equipment

The upper row in Figure 3-8 illustrates (from left to right):

- A dc servo (with drum and bracket assembly) - used as a parallel servo for elevator, aileron, rudder, flap and elevator trim.
- Vertical Gyro
- AC servo - used for autothrottle and nozzle servos
- 1819A Computer Panel - ground support equipment that is not used in the airborne system

The middle row illustrates:

- Panel Power Supply - a similar package houses the Servo Interlock Unit
- 1819A Computer
- Auxiliary Memory Unit (contains additional 16K core plus magnetic tape controller electronics and growth space)
- Data Adapter
- HSI Instrument Amplifier (for RD-200 HSI)

The bottom row illustrates:

- Status Panel and Keyboard - Early designs are shown. They have now been superseded by the units illustrated in the previous photographs of the Sperry Validation Facility cockpit and in Figure 3-9.
- EADI - (note the MFD is not shown here)
- RD-200 HSI

The Status Panel and Keyboard are shown on Figure 3-9. They provide the interactive control and display used to communicate with the STOLAND system for those functions which are not covered by direct controls included in the Mode Select Panel or MFD Controller. An example of such communication is the entry of waypoint coordinates. Another example is illustrated in the previous figure of the Sperry validation facility cockpit during a flight on

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Figure 3-8
Photographs of STOLAND Equipment

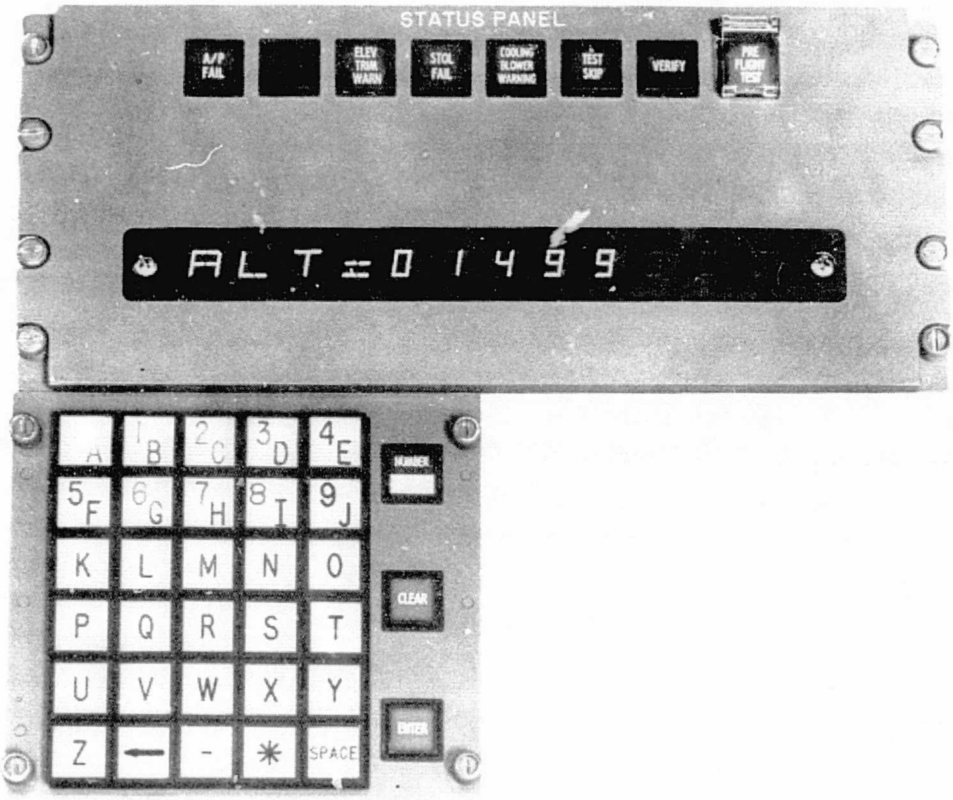

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Figure 3-9
Status Panel and Keyboard

the reference flight path where the Status Panel alphanumeric display reads WPT = 9. This indicates that the system was instructed to capture the sequence of waypoints at the segment approaching waypoint number 9. The pilot keyed in WPT and entered the desired entry point as 9. When he was satisfied that the 9 appeared, he depressed the ENTER button, thereby enabling the flight path capture sequence.

Another use of the Status Panel is for administering the automated preflight test of all the STOLAND LRUs. Depressing the guarded preflight test button (enabled only with weight on wheels) starts the test. When the operator is required to participate, instructions appear on the alphanumeric display. An example of such an instruction would be "push column" or "pull column" to test maneuver force transducers. Another example would be to depress illuminated pushbuttons as they sequentially illuminate. If the computer response is to disengage a solenoid hold switch or illumiate a warning light, the test operator is asked to verify the desired response by depressing the VERIFY pushbutton. If a test failure occurs, the STOL FAIL pushbutton illuminates, the test sequence stops, and an LRU failure message appears on the display. Depressing the STOL FAIL pushbutton interrogates the computer to identify the nature of the failure. The response is a diagnostic number which can generally be correlated to a subassembly level in the failed LRU. To continue the test, the TEST SKIP pushbutton is depressed. If another failure is encountered the annunciation sequence is repeated.

When the end of the test is reached, if there were no failures, a STOL PFT OK message will follow. If failures occurred, the number of failures would be listed with a message such as 4-FAILURES. If the STOL FAIL pushbutton is then depressed repeatedly, a sequential listing of the specific failure diagnostic codes is displayed. Depressing the PRE-FLIGHT pushbutton after all the diagnostics have been reviewed will clear all failure data that is stored and the test and fault isolation procedure will be repeated.

The test program is written in sections so that the first test sequence, performed in about 3 seconds, checks most of the system without requiring operator participation. At the completion of this phase, a

displayed message gives the option of continuing the more detailed operator participation tests or bypassing them by depressing the TEST SKIP button. The detailed test can be completed in about 15 minutes.

Similar failure messages are used to annunciate in-flight failures detected by the system's monitoring algorithms. Thus, for example, a roll rate gyro wheel bearing failure would cause removal of that device's VALID discrete (detected by the spin motor rotation detector). The absence of that valid in the computer logic equations would cause the disengagement of the autopilot roll axis, display of the STOL FAIL amber light, a flashing red warning light on the instrument panel and, when STOL FAIL is depressed, display of the message: ROLL GYRO.

Figure 3-10 shows the MFD Controller and Mode Select Panel. Both of these panels are completely under software control and the legends and switches may be readily changed. The MFD Controller is used as a map control with the following capability.

The three-map orientation pushbuttons select COURSE-UP, HEADING-UP and NORTH-UP (fixed map, moving aircraft). The map slew joy stick moves the map at a fixed rate in response to the four directions of stick movement. If the airplane symbol is driven off scale, depressing any of the map scale pushbuttons (.5, 1.5 and 5.0 nautical miles/inch) recenters the aircraft in the HEADING-UP or COURSE-UP modes. The bottom left four switches select reference flight path experiments that can be reprogrammed as desired. The bottom right pushbuttons are used to select different map contents. This is a convenient means of editing clutter by selectively eliminating certain symbols.

The Mode Select Panel has three main configuration selectors at the top: FULL AUTO representing total automated flight capability, including all servos if selected through the appropriate procedures; FLIGHT DIRECTOR and STANDBY/ON. Reference parameters such as Indicated Airspeed (IAS), Flight Path Angle (FPA), altitude (ALT), heading (HDG) and course (CRS) are displayed in reference windows. The knobs at the side of the reference display permits pilot change of the selected reference. In the fully automated

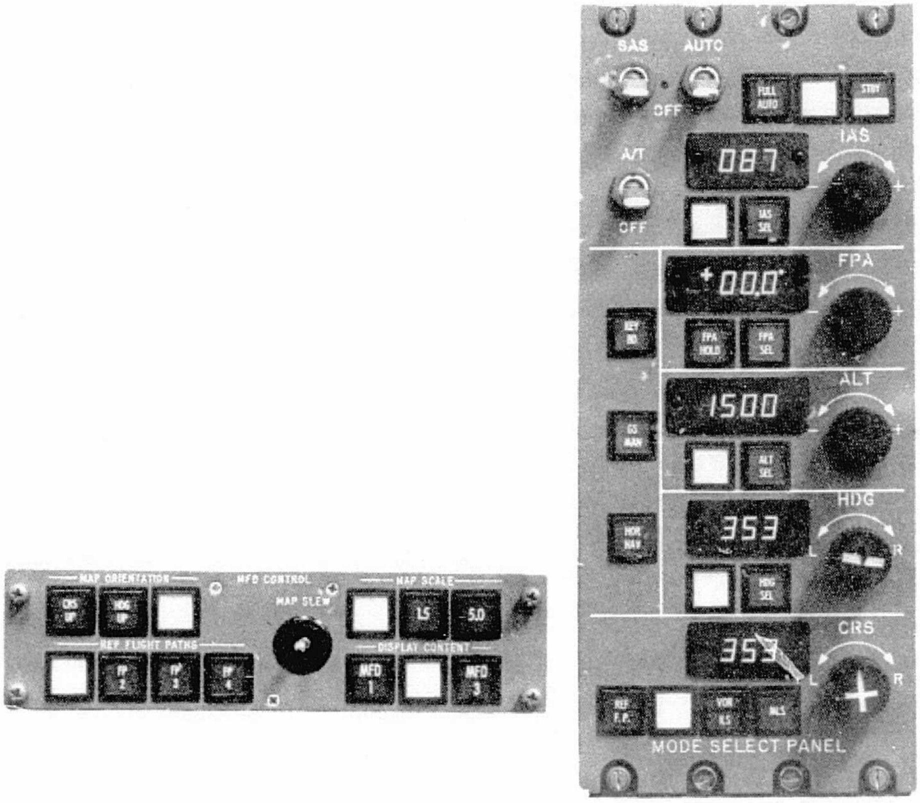

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Figure 3-10
Photographs of MFD Controller and Mode Select Panel

flight modes, the flight path reference parameters are set by the trajectory generation program and transmitted to the appropriate reference windows.

Figure 3-11 illustrates the STOLAND installation in the Buffalo/ Augmentor Wing cockpit, showing the EADI, RD-200 HSI, MFD, MFD Controller and Mode Select Panel on the Instrument Panel and the Status Panel and Keyboard in the pedestal area. Space limitation prevents the MFD map from being located under the EADI.

The STOLAND installation in the cockpit cab of the NASA/Ames simulator facility is shown in Figure 3-12. This equipment was operating with the remaining hardware, airborne software and the NASA simulation about one year after program authorization.

12. System Architecture

a. System Block Diagram

Figure 3-13 illustrates the data flow between the various STOLAND LRUs. The "Computer Complex" or main core of the system contains the Digital Computer, the Auxiliary Memory unit and the Data Adapter. It isolates the computer from all electronic mechanization problems so that the computer's contribution to the system is contained entirely within its software. The Data Adapter serves as a communications terminal for all data transfers and as a data conditioning and conversion center for the computer. It interfaces directly with all system sensors required for software computations. It also interfaces directly with certain low current output loads and via the Servo Interlock Unit with high current loads. The Data Adpater is very versatile because it has modular circuit construction and built-in spare capacity to facilitate substitution or addition of interfacing devices.

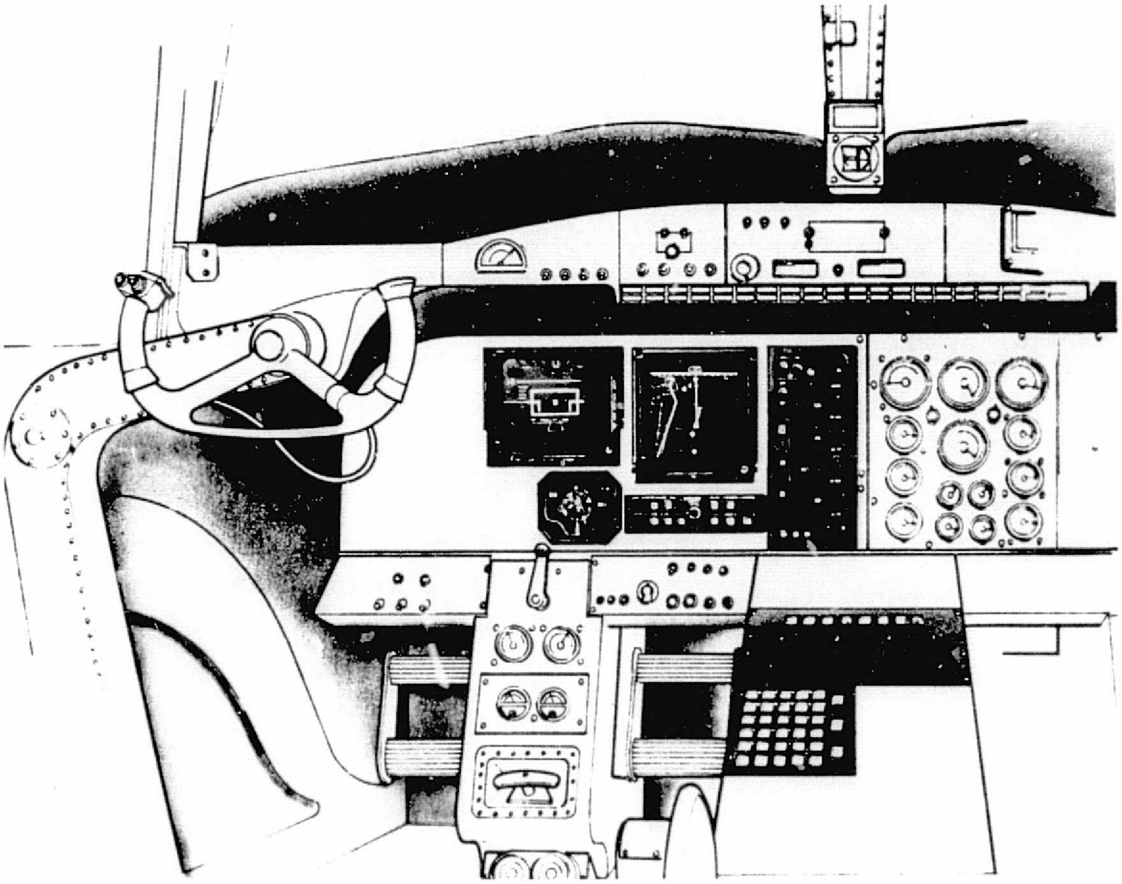

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Figure 3-11
STOLAND Installation in the Buffalo Augmentor Wing Cockpit

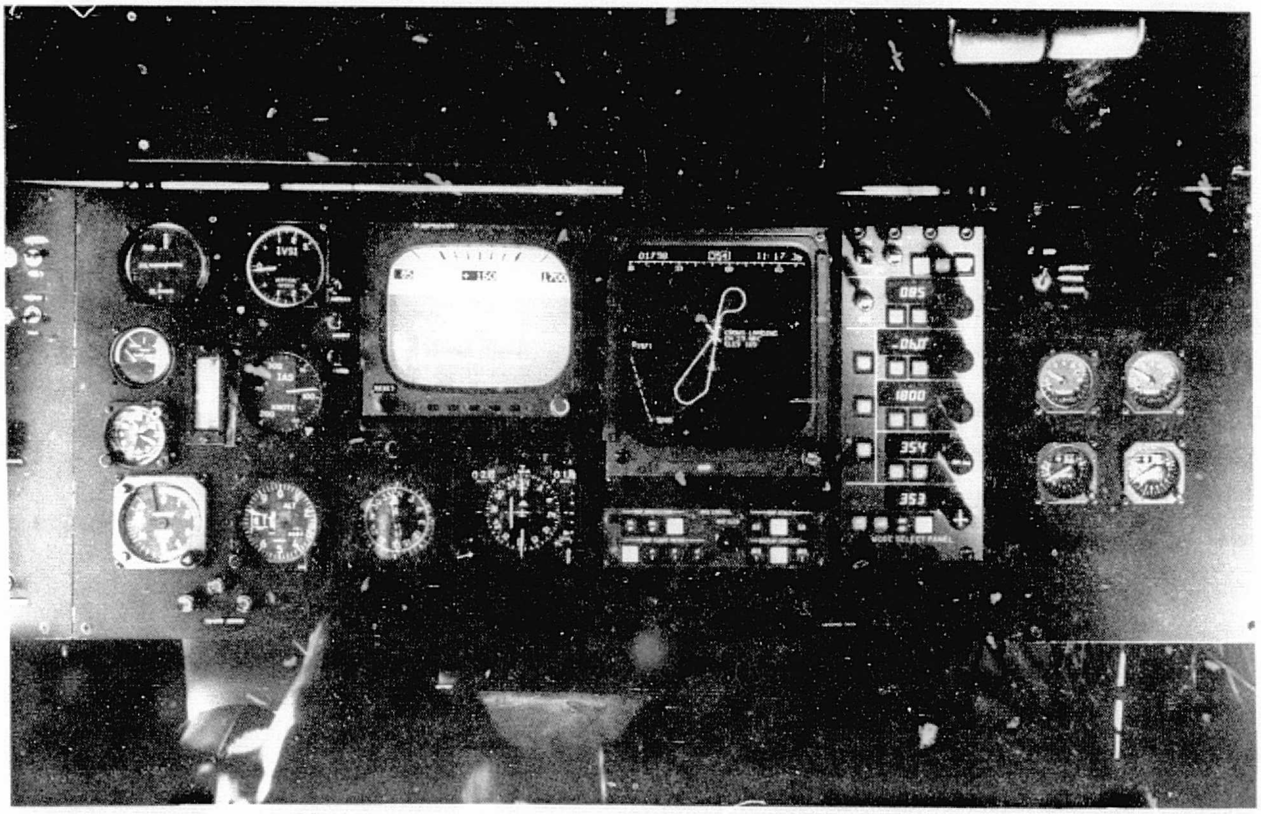

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Figure 3-12
STOLAND Cockpit Installation in NASA Simulator

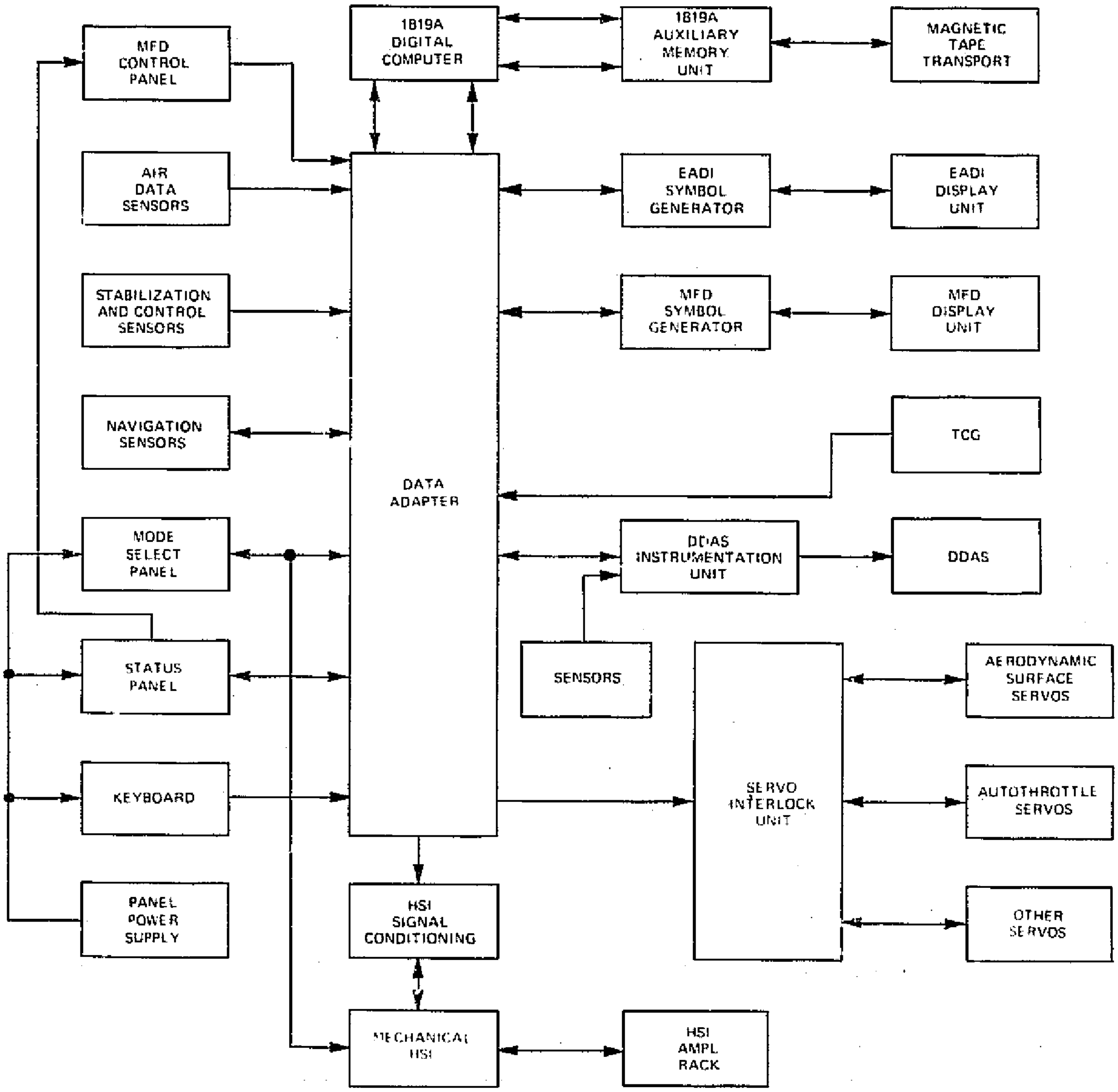

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Figure 3-13
System Block Diagram

Communication with the computer is by means of high speed, parallel 18-bit and 36-bit data transfer. The computer complex outputs (via transmitters in the Data Adapter) a stream of serial data onto its output data bus. Communication with panels and displays are through this one-way data bus. The following is a partial summary of Data Adapter functions:

- Analog Sensor Interface - All sensor signals are coupled into the Data Adapter via differential input buffering. Demodulation, scaling and signal conditioning are performed as necessary prior to multiplexing the signals and converting to digital format for transmision to the digital computer.

- A/D Multiplexer and Converter - Each analog input is assigned a specific location on the A/D multiplexer. A/D conversion is accomplished under software control. Each multiplexer position may be sequentially or randomly accessed. Completion of each encoding process by the A/D converter results in an encode complete signal to the I/O control which activates the control lines needed to initiate the transfer of data to the computer.

- Discrete Input Interface - All system logic discretes required in the software computations are conditioned within the Data Adapter. Discrete data is formatted and packed into unused bit positions in the A/D words.

- Digital-to-Digital Data Handling - Serial digitial data is received asynchronously from several sources (DME, MLS, TACAN, operational INS and external computer systems). Parallel digital data is received from the MLS and Time Code Generator (TCG). Parallel digital outputs are made to the Digital Data Acquisition System (DDAS) and to the magnetic tape controller. Serial digital outputs are generated for the STOLAND primary data bus and auxiliary bus (to the MFD). The multiplexing of

all digital input data for transmission via a single computer I/O channel and the timing and control of the digital data acquisition and distribution is part of the digital-to-digital data processing function.

- Analog Outputs - D/A words are transmitted synchronously from the computer under software control. The Data Adapter I/O control steers these words to the appropriate buffer registers, one for each D/A output, and these D/A registers are refreshed at the program iteration rate. Unused bit positions on the D/A words transferred from the computer are packed with discrete data, which is unpacked in the Data Adapter and coupled to external loads via discrete output drivers.

The Servo Interlock Unit provides the power drives for operating the various servo systems. It receives position or velocity commands from the D/A output channels of the Data Adapter. The STOLAND system drives up to 12 servo actuators. It is noted that the system is partitioned so that only the Servo Interlock unit (SIU) needs be changed when installations in different aircraft are considered. The SIU must be tailored to each individual aircraft's unique flight control actuation requirements. Nevertheless, the SIU has modular circuit construction and has built-in adaptability to other aircraft.

The system block diagram illustrates an avionics architecture concept which is one of the most significant achievements inherent in the STOLAND design. STOLAND accommodates a diverse set of input and output devices. These devices and subsystems represent just about every type of navigation, guidance control and display equipment in the 1973 avionics technology (with the exception of radar and laser sensors). They all have their unique interface requirements. They were procured as off-the-shelf equipment and no attempt was made to dictate design changes to these devices in order to simplify interfacing them into the computer complex. The Data Adapter converges a chaos of signals and asynchronous digital data with all

types of format into an orderly flow of information to and from the digital computer. Subsequent discussions will describe how some of this information flow is accomplished.

b. STOLAND Computer I/O Channelization

The STOLAND computer has seven I/O channels to enhance high speed data transfer with a minimum of software and external hardware complexity. The data lines of all seven channels are multiplexed within the computer to a common party line, but separate control lines for each channel permit recognition and distinction of external data without necessitating complicated external addressing schemes or resorting to external interrupts and the concommitant time penalty.

As seen in Figure 3-14, channel 1, a 36-bit channel (plus separate control lines) requires a multiplexing subsystem within the Data Adapter. This will be descibed later. Channel 2 handles all A/D and D/A information transfers under software control and synchronized with the computer program. (All of the channel 1 input data transfer is asynchronous with the computer program.)

Channel 3 allows the tie-in of peripheral equipment for software development. It is significant to note that all software development is performed on-line. Thus, the 1819A airborne computer also serves as a stand-alone computer able to perform all of its own software development. This includes program assembly and editing with on-line editing capability for object program. The Auxiliary Memory Unit holds the assembly programs, utility programs and all support software that permits tie-in to the various peripheral equipment. When the airborne program is resident, the utility programs for debugging and editing are also resident and communication with the peripheral equipment at that time is through channel 3. Channel 4 is reserved for a special direct digital interface with the simulation computer, a valuable asset during simulator testing.

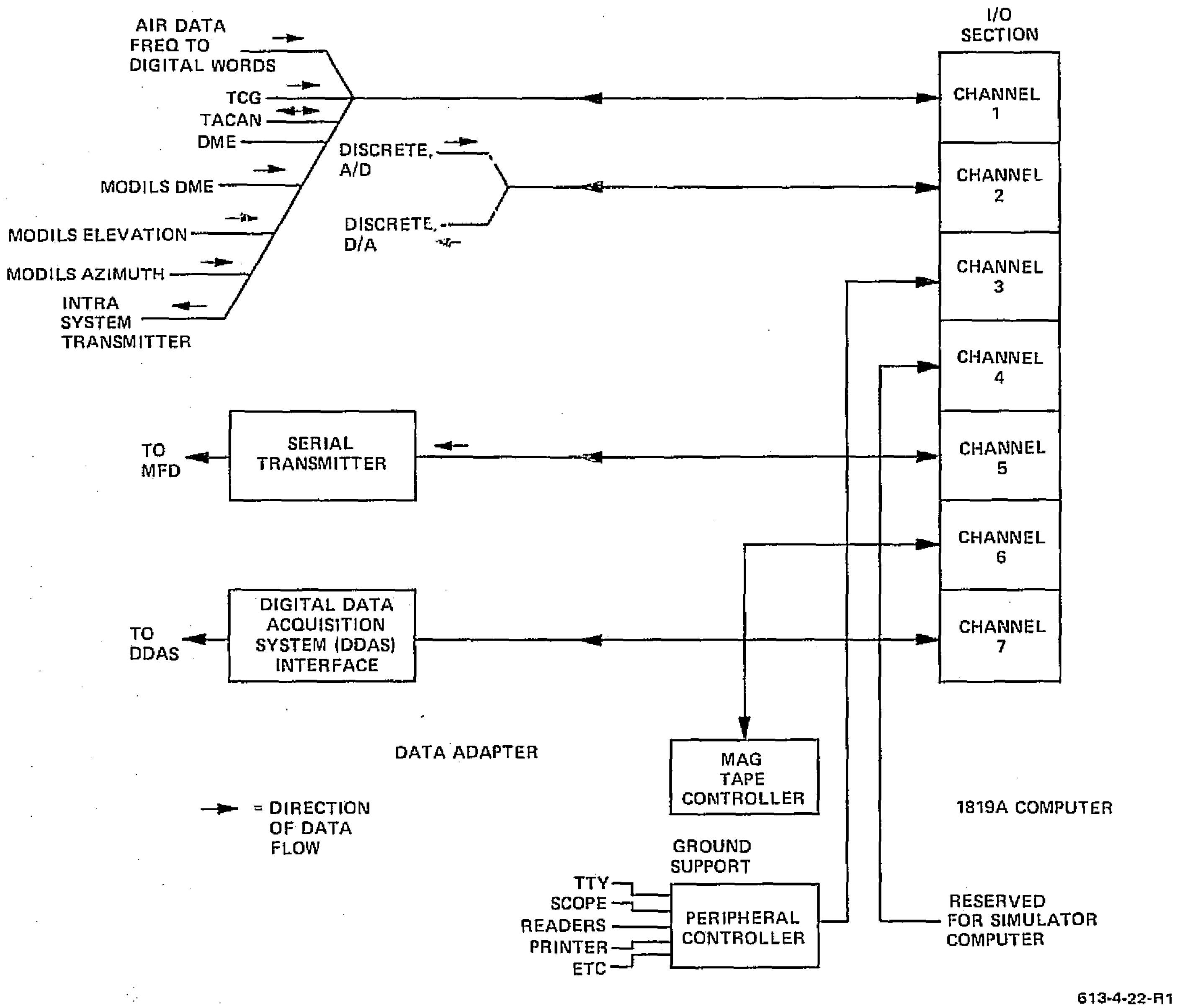

Figure 3-14
STOLAND Computer I/O Channelization

Channel 5 is used to communicate with the MFD. This channel could have been eliminated and the serial output bus on channel 1 used for MFD data transmission, but this would have necessitated increasing the data rate on the bus; a change easily accommodated by the STOLAND serial data transmitter, but one that would have necessitated a design change in the MFD Symbol Generator.

Channels 6 and 7 are accessed by the same I/O buffered words. The nominal word rate to both the magnetic tape (CH 6) and the DDAS (CH 7) is approximately 1000 words per second.

c. Basic Word Format and Split Phase Bipolar Modulation

Figure 3-15 illustrates the format used for serial data transmission within the STOLAND system (communication tc panels and displays). The so-called split phase bipolar format is equivalent to the Manchester bi-level format used in several military avionics systems (except for the half pulse width dwell at zero .... this feature simplifies clock extraction). It is operated in the STOLAND system at a 50-KHz bit rate, but it has been successfully operated at 500 KHz.

d. Digital Input Channel Subsystem Block Diagram

Figure 3-16 illustrates one type of function performed by the Data Adapter, specifically the multiplexing of digital input data from the eight sources identified on the diagram. The point emphasized by this illustration is the modular versatility of the data handling. There are eight separate input data sources using seven different input processing mechanisms but all transfer data to the digital computer via the same 36-line drivers (I/O Interface cards) under control of the digital multiplexer which is designated "Digital Control" in the figure. The digital control uses the computer channel 1 input data control lines (Input Data Acknowledge - IDA, Input Data Request - IDR, External Function Acknowledge - EFA) to communicate with the computer and determine when to connect the selected data on the I/O data lines.

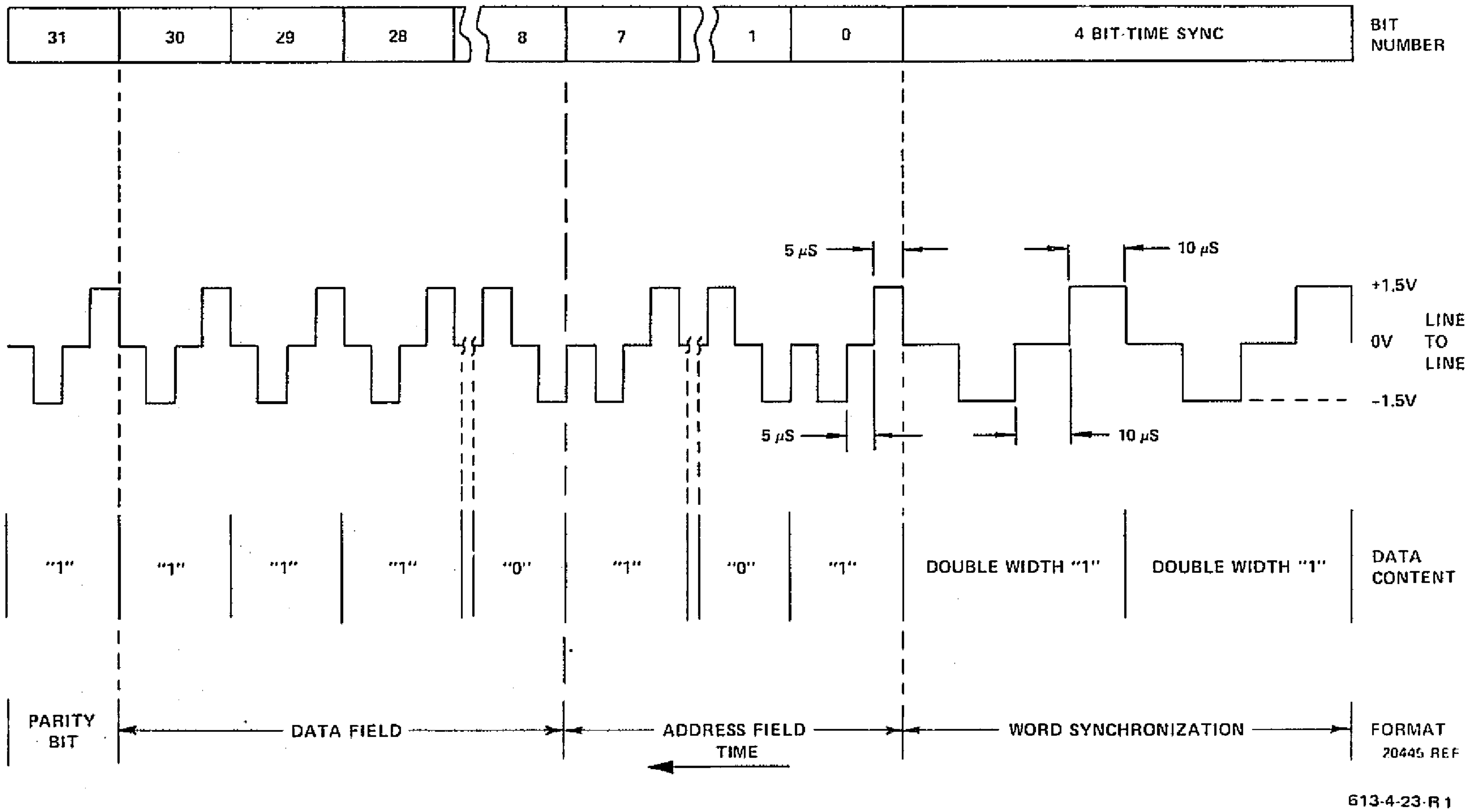

Figure 3-15
Basic Word Format and Split Phase Bipolar Modulation

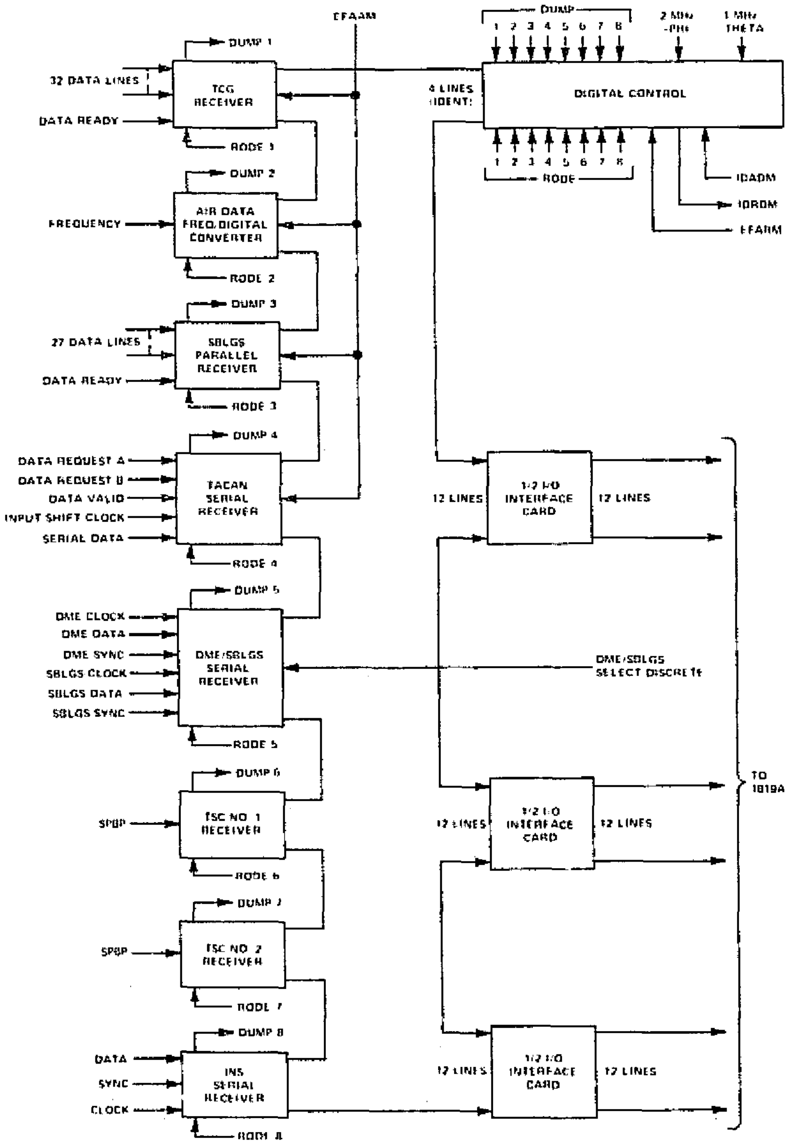

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Figure 3-16
Digital Input Channel Subsystem Block Diagram

The variety of input formats is apparent. The Time Code Generator (TCG) has 32 data lines and a data ready control line. The air data frequency-to-digital converter accepts an audio signal input. The converter contains a zero crossing detector that gates a 37.5 MHz clock through a high speed 21-bit counter for a prescribed 100 period count and transfers the 18 most significant bits to the computer I/O lines when the digital control recognizes the count complete (DUMP 2) and after obtaining an open I/O line via the input data request and acknowledge sequence. Data transfer is accomplished through the Receiver Output Data Enable (RODE) line which the digital multiplexer sets (RODE 2 for the case of the air data word).

The MODILS system (Scanning Beam Landing Guidance System - SBLGS) has parallel and serial data inputs. This interface is obviously not a good one for a digital system (27 parallel data lines for elevation and azimuth angle data) but STOLAND was required to accommodate the existing MODILS design. The serial part of the MLS interface is for the MLS DME data. Here an ARINC 561, 6-line (12-wire) serial format is used. The receiver for this data is shared with the conventional DME since only one DME source is used at one time.

Two receivers designated TSC No. 1 and No. 2 are shown. These Split Phase Bipolar (SPBP) data receivers are provisions for interfacing the FAA Transportation System Center's (TSC) experimental navigation inputs for future NASA experimental evaluations. Similarly, the INS receiver represents provision for future experiments to evaluate the performance improvements obtainable with an INS (in this case the ARINC 561 6-line interface again).

e. TACAN Interface Block Diagram

Figure 3-17 illustrates the TACAN interface for the off-the-shelf Hoffman Micro-TACAN Receiver. The STOLAND computer program generates a request for fresh TACAN data each iteration cycle via the External Function Acknowledge (EFA) line which is gated to the TACAN control by the input digital data multiplexer described in the previous figure. A valid data response from the TACAN set will allow the TACAN control to transmit a shift clock (generated from the 1 MHz, two-phase clock) to the TACAN set which in turn uses that clock to shift out 28-bit serial words (bearing and distance).

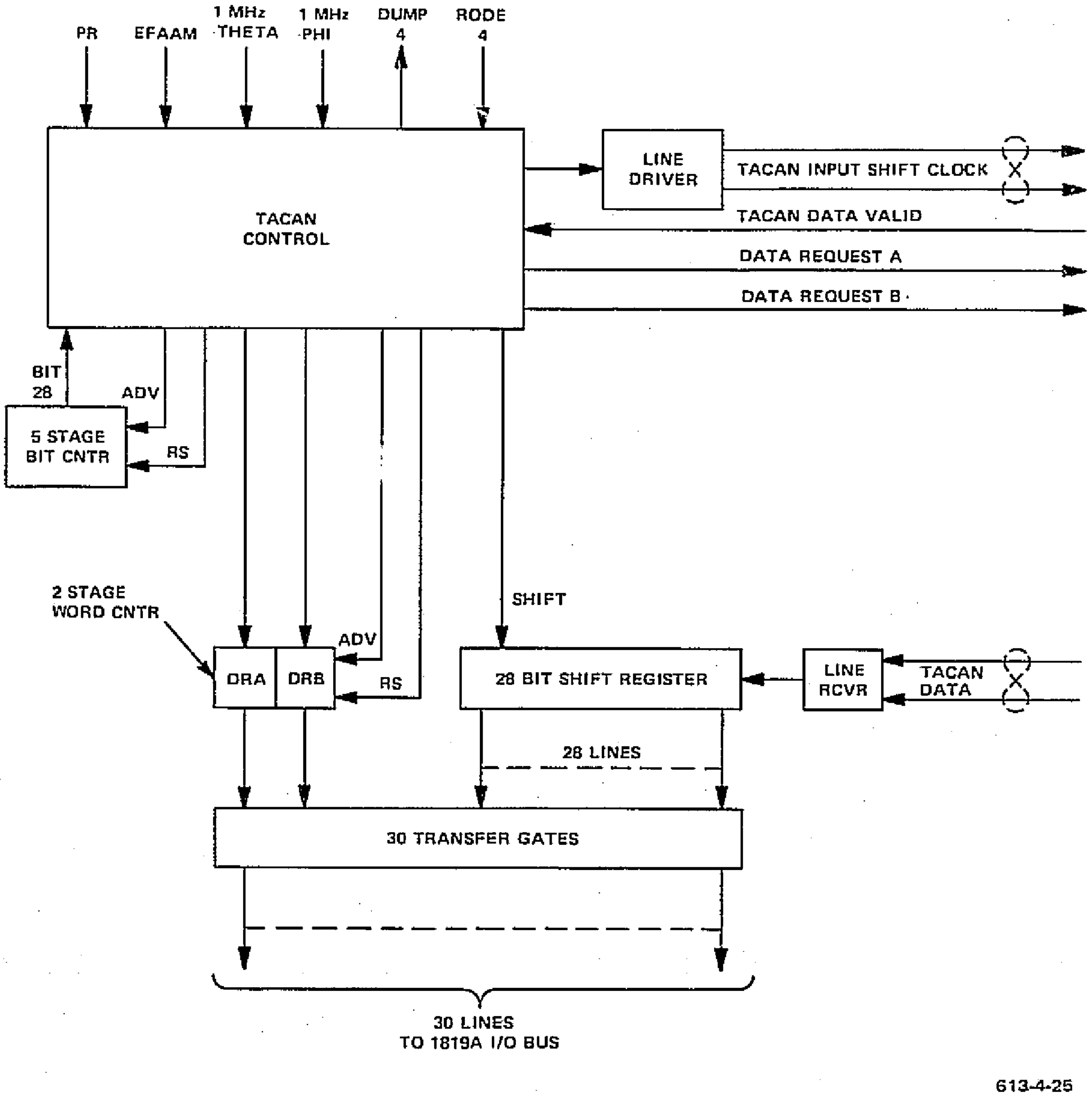

Figure 3-17
TACAN Interface Block Diagram

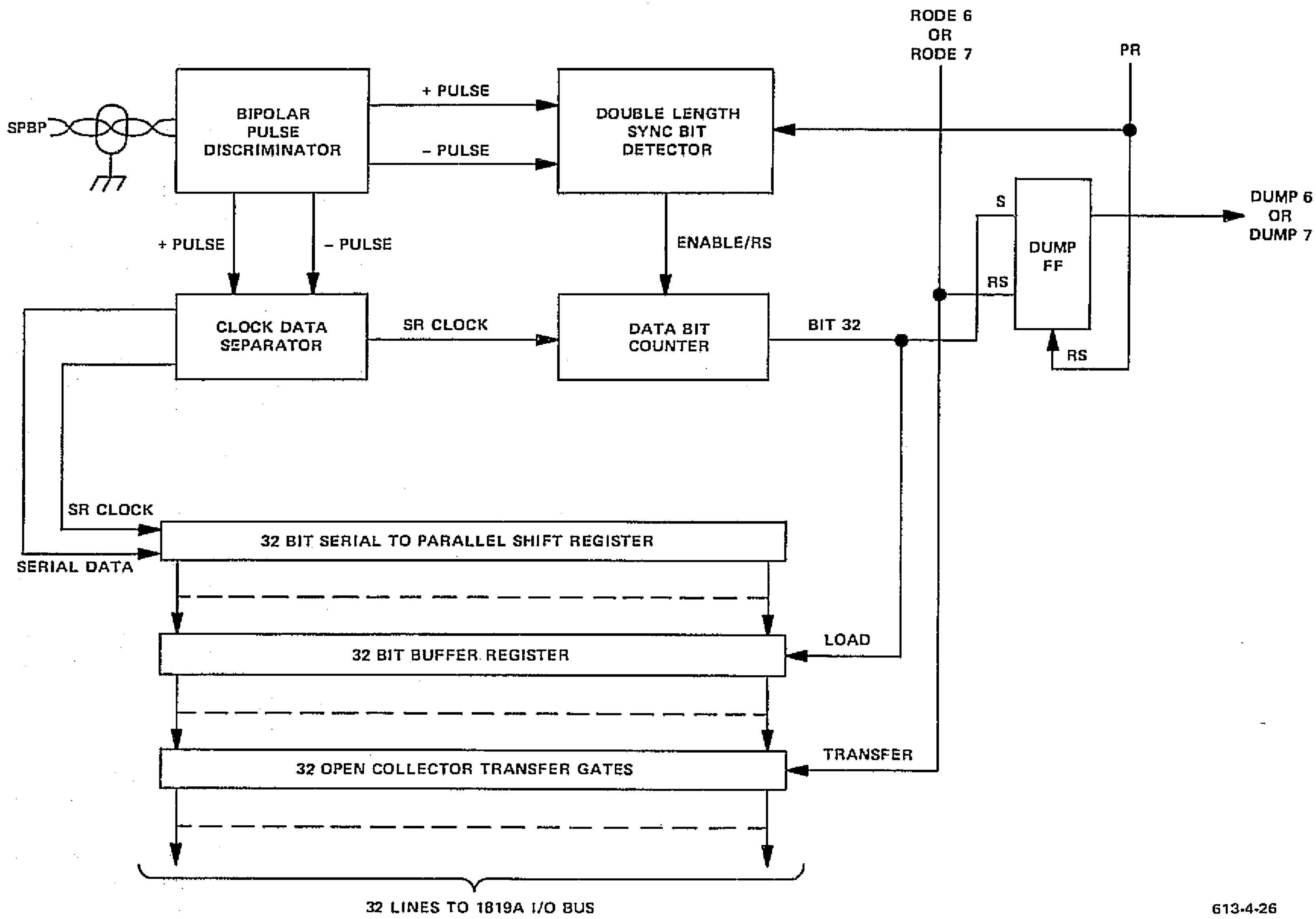

Figure 3-18
SPBP Receiver Block Diagram

These are received in a line receiver and input shift register and with the addition of a 2-bit identity tag, the data is placed on the computer I/O bus following the DUMP and RODE communication sequence with the input digital data multiplexer described previously.

f. SPBP Receiver Block Diagram

Figure 3-18 shows the Split Phase Bipolar (SPBP) receiver which is used for the TSC interfaces and for all internal STOLAND communications. That is, it is used by the panels, the MFD and EADI to receive computer-generated data.

In contrast to the TACAN interface, this receiver generates a 32-bit word and requires a clock/data separator and word synchronization discriminator in lieu of the two-way data control communication of the TACAN interface. Note also that although the word length is 32 bits, the input digital data multiplexer adds four additional identification bits to create a 36-bit I/O word. The additional four bits are used in the software routines for data unpacking. Word format and timing is shown on Figure 3-15.

g. Serial Digital Output Channel Subassembly Block Diagram

Figure 3-19 is a simplified schematic of how the computer output data is steered through line receivers to two serial transmitters. As stated previously, a single transmitter operating at twice the speed could have been implemented, but it would have necessitated design changes in the existing MFD. The transmitters are reset each computer iteration cycle by the External Functional Acknowledge (EFA) control line. The Output Data Request (ODR) and Output Data Acknowledge (ODA) control lines to computer I/O channel 1 controls the dumping of data by the computer onto the I/O bus (and hence to the transmitters). PR is a power test input.

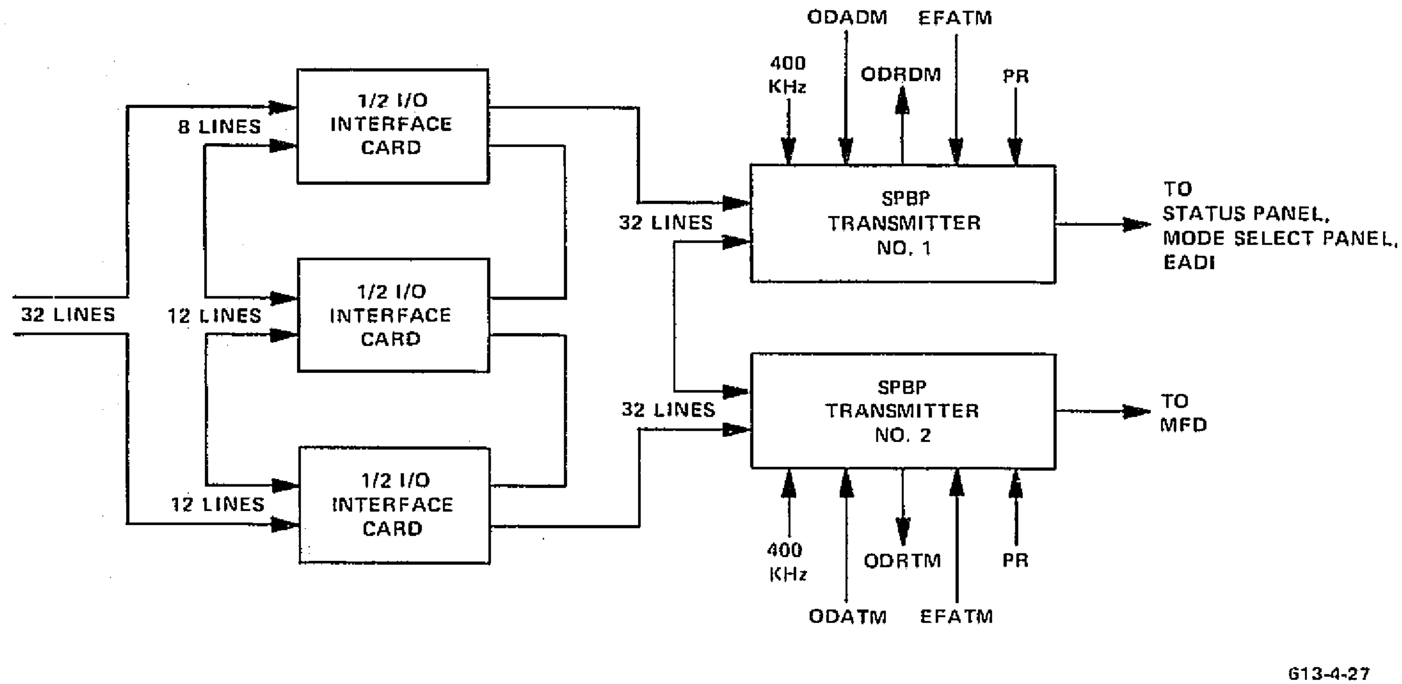

Figure 3-19
Serial Digital Output Channel Subassembly Block Diagram

h. SPBP Transmitter Block Diagram

Each of the transmitters of the previous figure are implemented as shown in Figure 3-20. If a different format or different type of transmitter is desired, only the transmitter card is changed in the system.

i. Analog, Discrete and Parallel Output Channel Subsystem Block Diagram

The system's required analog outputs are controlled by the analog output control. This function interfaces with the computer's output data control lines. The numerical sequence of output words is software controlled. The analog output control multiplexes the various D/A registers onto the I/O data lines via its enable lines. Shown in Figure 3-21, the analog output configuration uses 10-bit D/A outputs (for eight servo commands and two HSI instrument scales).

The output discretes are packed by the software into 4 bits of the 18-bit data words. Five data words dedicated to discretes alone therefore provide 20 output discretes. Discretes are also packed with 4 bits of the ten analog data words adding an additional 40 output discretes and making a total of 60. The I/O discrete conditioning is tailored to the specific 15 volts, 28 volts and ground discretes of the STOLAND system.

Several higher accuracy D/As are required for digital-to-synchro conversion of the HSI information. Since the digital-to-synchro conversion also requires significant output drive power, the separate HSI Signal Conditioning Unit is required. The necessary high accuracy D/A converters are located in that LRU and the specific words required are steered through the Data Adapter by the analog output control to line drives for transmission to the HSI SCU.

13. Software

a. STOLAND Software Summary

Table 3-2 summaries the software time and memory requirements for the STOLAND application in the Augmentor Wing.

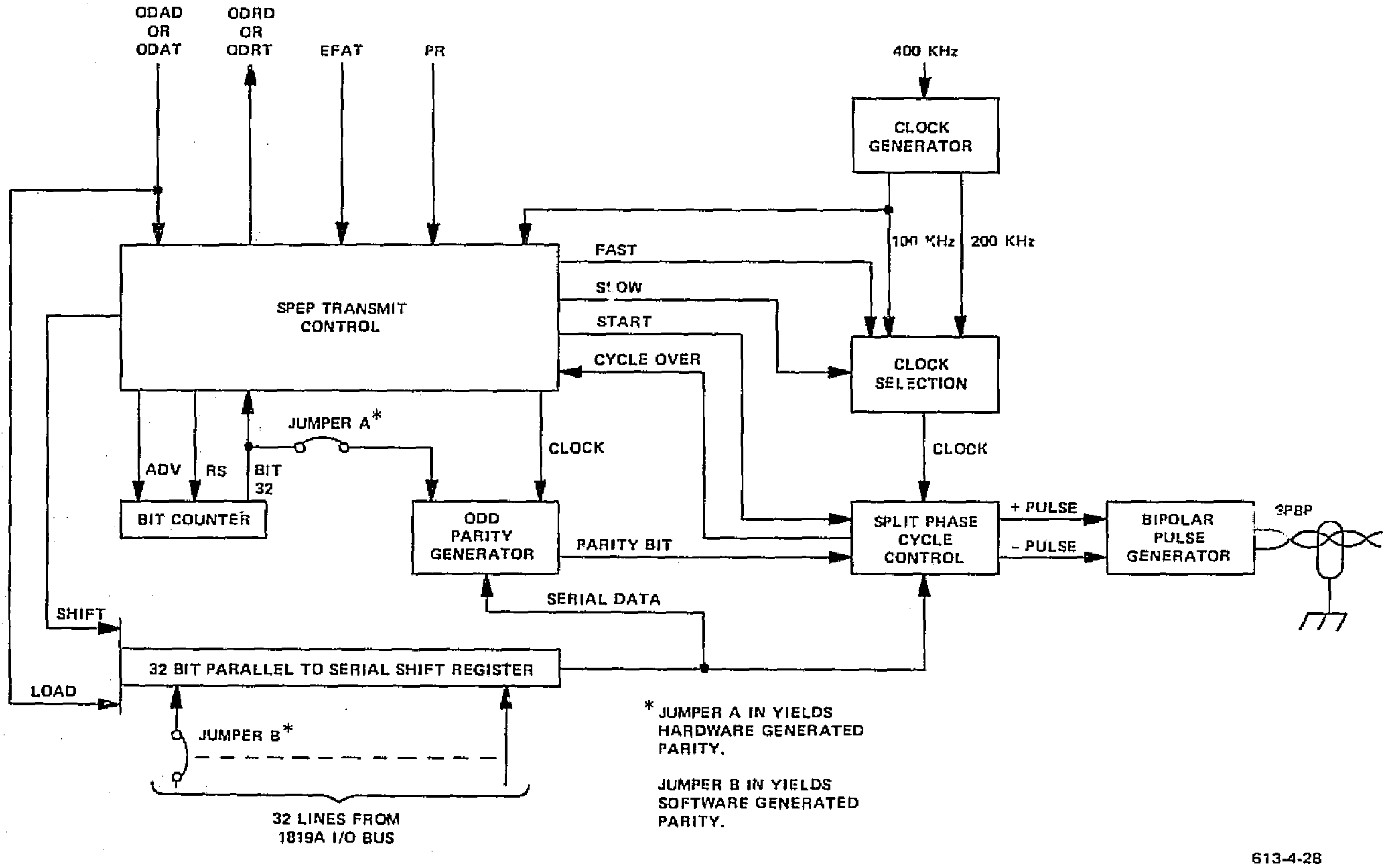

Figure 3-20
SPBP Transmitter Block Diagram

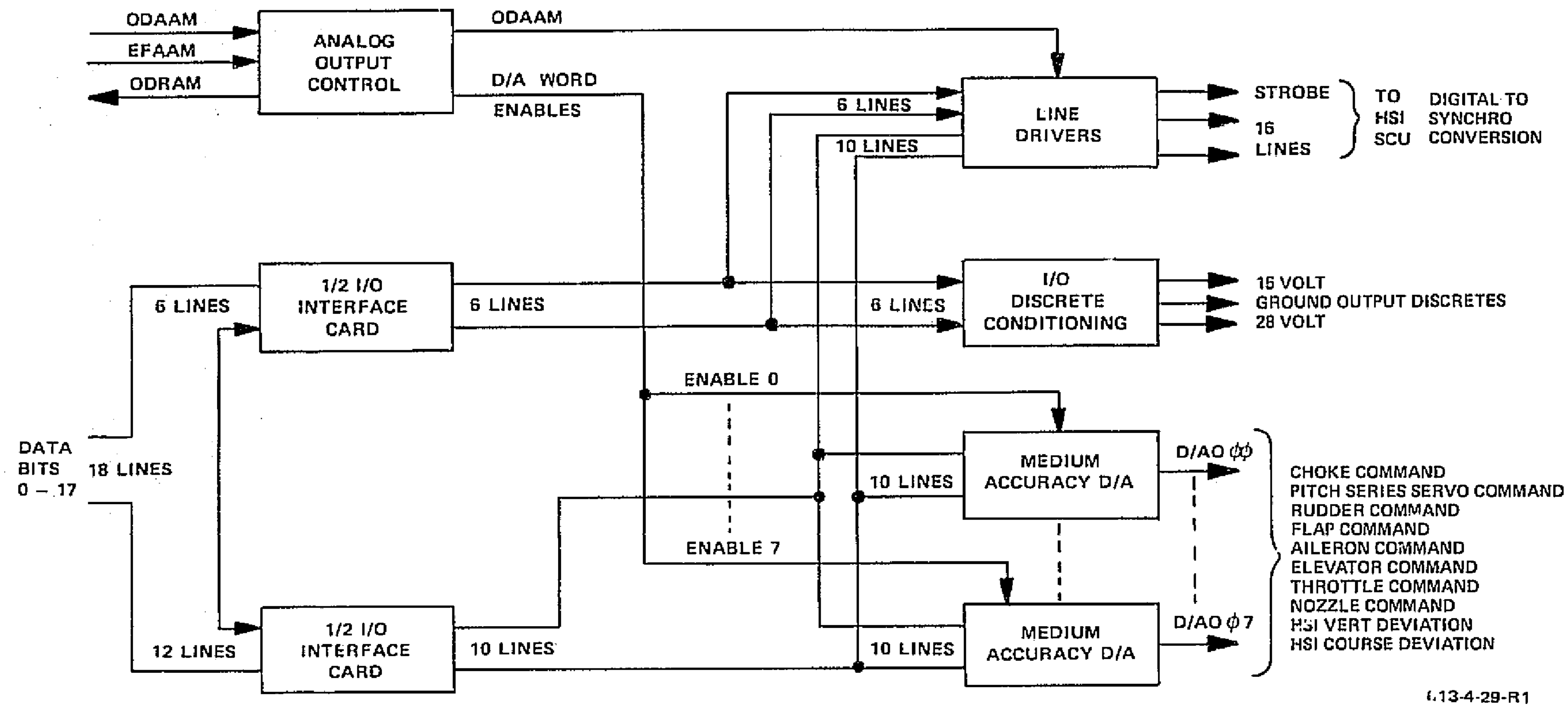

Figure 3-21
Analog, Discrete and Parallel Output Channel
Subsystem Block Diagram

TABLE 3-2

STOLAND SOFTWARE SUMMARY

Function	Time/ Solution (msec)	Iteration Rate	Time Consumption (msec/sec)	Memory Usage (words)
Master Executive and Timing	1.2	20/sec	24.0	374
Input/Output	5.6	20/sec	112.0	339
Monitors and Diagnostics	1.5	20/sec	30.0	619
Keyboard and Status Panel Number Entry	.052	20/sec	1.04	1,453
Decode/Display	2.304	20/sec	46.08	
Mode Select panel and Mode Interlocks	1.3	10/sec	13.0	1,762
Navigation	6.0	20/sec	120.0	1,066
Air Data Computation (h, V_C, V_T, Q, T_T, T_S..)	1.3	20/sec	26.0	132
Attitude Stabilization Control Stick Steering and Flight Director	3.7	20/sec	74.0	880
Autopilot and Autopilot Executive (includes Trim Tables)	4.0	20/sec	80.0	3,134
Electronic ADI (including Runway Perspective Display)	4.19	20/sec	83.8	561
3-D Guidance	2.0	10/sec	20.0	1,785
4-D Guidance	1.2	.1/sec to 10/sec	12.0 (max)	1,304
Multifunction Display (MFD)	6.0	1.0/sec and 20/sec	120.0 (max)	3,636
Horizontal Situation Indicator	2.3	10/sec	23.0	230
Magnetic Tape and Digital Data Acquisition	1.2	20/sec	24.0	495
Speed Control....Autothrottle Flap, Nozzle, etc	1.4	20/sec	28.0	356
Data for all Modules (except 3D-4D and MFD)	--	---	---	3,542
Totals			835.92 absolute max	21,868
Preflight Central Integrated Test				2,558

The master executive and timing and input/output modules include the housekeeping functions such as I/O control, data entry, unpacking, packing and formating and a considerable amount of mode logic associated with the panels.

The requirements for navigation seem quite small but it should be understood that navigation in this table refers only to the solution of the Rho, Theta trigonometric equations and state estimation filter equations. The data acquisition, mode selection, etc, have all been covered in the housekeeping functions mentioned.

The Flight Director functions include only the special adaptations of the autopilot guidance laws needed to generate the required steering cues. That is, most of the accepted control laws for a flight director would be found in the autopilot and 3-D guidance summary plus some additional contributions obtained from the navigation filters and mode logic equations summarized on the previous chart.

The distinction between autopilot and 3-D guidance is not clear cut. In this summary the autoplot items refer primarily to those functions seen on the Mode Select Panel. The 3-D guidance refers primarily to the storage and processing of arrays of data associated with waypoints that define reference flight paths. The 3-D guidance program reduces the waypoint data to flight path guidance program equations which are common with the guidance equations used in the autopilot routines.

The largest memory consumer is the MFD. This is associated primarily with the storage of map data and the transformation of waypoint-defined flight paths into the map coordinates.

The relatively large ratio of time to memory for the Horizontal Situation Indicator occurs because the processing of information to drive this instrument involves a considerable amount of trigonometric functions that are time consuming.

The totals show that the absolute worst case time consumption is about 83 percent of available time with 21,868 words of the full potential of about 31,000. (Some of the 32,768 words are hard wired for specific use such as BITE.) The 2,558 word preflight integrated test is presently stored in core memory. If this memory space should be required to perform future flight experiments, the preflight test could be stored on the magnetic tape and loaded only when the test is being performed.

b. Programmer Support Routines

Software development is done using the STOLAND digital computer for assembling, debugging and editing. The support software operates with a variety of selectable peripheral equipment (magnetic tape, paper tape, cards, line printer, TTY, CRT consoles) and includes the following:

- SNAP Assembler Program
- SNAP Editor
- Track Diagnostic Program
- UTIL-Conversational Utility Program

Programs are written in a simple instruction format assembly language, and machine language tapes are generated by the two-pass SNAP assembler. Software is available for magnetic tape, paper tape or punched card operation. The SNAP editor allows additions, deletions insertions and corrections on the source program.

The object tapes (machine language programs) are debugged and edited with a versatile conversational utility program designated EXUTIL, a combination of the Track Diagnostic program and UTIL. This editing is usually done on-line with the airborne program and all software tied together.

EXUTIL is maintained resident in the airborne computer during program debugging and testing. It takes about 3500 words of memory, and resides in a 4K bank of the computer.

The capability of the utility program is summarized below:

- Octal or mnemonic inspect and change
- Decimal input and output
- ASCII input and output
- Search and change under mask
- Move block of memory
- Store constant in block of memory
- Subroutine call with preload
- Side-by-side or core dump listing
- Tags and labels
- Tape load, verify and generation
- Optional input source
- Optional output devices

The octal or mnemonic inspect and change is a basic editing capability. Keying in a given location (on the TTY or CRT terminal) results in a printout of the octal contents of that location. Depressing various specified keys causes either the decimal equivalent, the packed ASCII equivalent, the binary equivalent or the mnemonic representation of the equivalent instruction to be printed. The location may then be modified in the same format.

Search and change under mask allows any specified block of memory to be searched for any specified bit pattern, which, depending upon the mask, could be a search for a particular address, instruction or data.

Blocks of memory may be moved by merely specifying the present initial and terminal addresses of the memory block and then the desired new initial location. This is useful for inserting new sections of a program. Storing constants in a block of memory is a useful method of zeroing a large number of locations (a convenient debugging technique). Subroutine call with preload allows a newly written subroutine to be tested by conveniently

preloading all pertinent registers with a desired set of numbers. These preloaded numbers will exercise the subroutine, and return to the utility, printing out all pertinent registers.

Core dumps in a variety of formats can be called. The usual type is a side-by-side listing in octal and mnemonic form. For some additional memory consumption in the UTIL program, the listing can be given in terms of tags and labels rather than addresses. UTIL and EXUTIL provide for tape loading, verification and tape generation and operate from a variety of optional input sources (TTY, CRT, paper tape readers, magnetic tape) and output devices (TTY, CRT, paper tape punch, line printer, magnetic tape).

c. Software Configuration Management

Software development for the computer is performed directly on the computer with the aid of support software (editor, assembler, utility routines). (This support software has been refined after 9 years of usage to a very reliable and versatile tool.) The use of other computer facilities for software development is not required, nor is it recommended. The equipment used for software control and development is shown in the Testing Summary, Section IV. Data can be inserted either in the form of punched cards, paper tape, magnetic tape, CRT consoles or teletypes and can be dumped out on paper tape, magnetic tape and the line printer.

Software modification is perferably performed in the source program for documentation purposes. Simple modifications can easily be performed in the object program in a matter of seconds via the teletype or CRT console, but this procedure is employed only for temporary changes When changes made directly in the object program have become firm, the source program is modified to reflect these changes and then reassembled.

Modification of punched tape or magnetic tape source programs is done by loading the program into the computer, making the modifications through the CRT or teletype (utilizing the editor routine in the computer), and dumping the modified source program on punched or magnetic tape.

Transformation from one format (such as cards) to another can similarly be done on the 1819A computer, and does not require other computer facilities or conversion programs.

Assembly of the source program, to produce the executable machine-language object program, is accomplished by two passes of the source tape into the computer. The object tape is produced during the second pass, and if desired, a listing of both the source and object program, side by side, is simultaneously produced on the line printer. Finally, the object tape is loaded into the airborne computer.

Starting with a source program on magnetic tape, it takes a few minutes to produce an object tape, and load that object tape into the computer. The assembly rate of a source program on magnetic tape is limited by the line printer when such printout is desired. Without printout, assembly of a magnetic tape source into magnetic tape object is a matter of a minute or less.

Formal software configuration control is instituted after completion of a system acceptance test. Software documents are provided for functional modules of the system. (The software summary charts give examples of the present STOLAND software modules.) Each software module document contains:

- A detailed description of what the module accomplished functionally
- A list of the subroutines within the module
- Complete flow charts for the routines

This technique meets the pertinent objectives of MIL-STD-483.

After configuration control is formalized, the following procedures are followed:

- Source programs and object programs are identified by part numbers that correspond to the controlling specification and associated dash number. These numbers are coded directly on the tapes.

- Associated with each tape part number is a listing containing each machine code instruction, its associated memory location and a tag list for the instruction-memory assignments.

- To execute a change in the program it is necessary to use formal change order procedures which require appropriate approvals and require retention of a written record of the change and reproducible copies of the document prior to change.

SECTION IV

TESTING SUMMARY

A. INTRODUCTION

The STOLAND system was developed with the requirements for testing and validation determining many aspects of the system configuration. This system configuration allows airborne hardware and software to be used in a validation facility so that the entire system can be developed and tested dynamically with the aircraft simulation and all the control loops closed and with full pilot participation when required. Furthermore, the validation facility includes all the peripheral equipment needed to control and develop the system software so that the software changes required in software development and testing can be made expeditiously, directly on line at the validation facility in parallel with the development testing. The magnetic tapes which store the 1819A computer program are also written at this facility and can be loaded into the computer memory either at the facility or on the aircraft using the STOLAND airborne Magnetic Tape Transport. The validation facility also includes a very useful data reduction capability. Flight data, recorded digitally using the STOLAND airborne magnetic tape transport, can be reduced into analog strip chart recordings within minutes of a flight test.

As can be seen from the capability described above, STOLAND is self-contained and therefore entirely independent of any other programming and digital facilities.

The validation facility and software development facilities are described later.

The sequence of STOLAND testing, beginning with component development testing and ending with flight test is listed below.

- Component development tests
- Component acceptance tests
- Static system hardware acceptance tests
- Dynamic system development and testing
- Dynamic acceptance tests

- Aircraft installation test
- Preflight test
- Flight tests

The component development tests are those associated with the detailed hardware design in each LRU. They also include environmental testing (vibration and temperature) to which several LRUs were subjected. A great deal of expense was saved in the STOLAND program by not subjecting each LRU to formal qualification testing. The validity of the approach has been well proven by the resulting reliability of the hardware in the flight environment of three different aircraft during the last 2 years of flight testing at Crows Landing where high ambient air temperatures and vibration could have been a problem.

The component acceptance tests are the functional tests of each complete LRU to its functional test specification. All of these tests were initially conducted prior to delivery and are repeated in the field to confirm failure in an LRU and following repair. The initial functional tests were made at Sperry using manual test fixtures. Functional tests of LRUs in the field at NASA are made using the STOLAND Automatic Test Equipment (ATE). The ATE is described later.

Static system hardware acceptance tests were conducted at Sperry prior to delivery of each set of flight equipment. They consisted of end-to-end checks on the entire interconnected system and will be described later.

Dynamic system development and testing, including software and hardware was started at Sperry using the Sperry validation facility which includes aircraft simulation and full closed loop dynamic development and testing. Software development was later continued at NASA on the NASA validation facility following the delivery of the simulator STOLAND.

Dynamic acceptance tests using the NASA validation facility were conducted on both sets of flight equipment and software and on the set of simulator STOLAND equipment. The simulator airborne hardware is functionally interchangeable with the flight hardware and therefore provides spares support for the two flight systems. The Dynamic Acceptance Tests are described later.

Aircraft installation tests were made on the system installations in the CV340, the Augmentor Wing and the Twin Otter. These tests verified that the installation was compatible with each aircraft and that ground operation was correct.

STOLAND is a very complex system. Conventional preflight testing of such a system would involve complicated, lengthy procedures and be very time consuming. The STOLAND system carries with it a programmed preflight test which automatically leads the preflight test operator through a test sequence which thoroughly tests all of the system hardware prior to each flight. The test takes about 15 minutes to run and has proved to be very useful. Some details of the preflight test were discussed in Paragraph III B.11.

Flight tests were made on all three aircraft. Flights on the CV340 did not include an autopilot or autothrottle installation but provided a good initial checkout of the remaining STOLAND systems including flight director, navigation, guidance, air data, etc. Flight testing on the Augmentor Wing and Twin Otter was completed through to fully automatic 4D guidance and control and fully automatic landing. The flight testing is described later.

B. VALIDATION FACILITY

Figure 4-1 shows the integration and interrelatonship between ground support equipment and the airborne equipment to form the system validation facility at NASA/Ames. This facility includes a special interfacing system designed by Sperry which ties the existing NASA aircraft simulation computer to the airborne equipment and to the software development equipment as shown in the figure. Similar facilities are also used at Sperry for integrated system and software development.

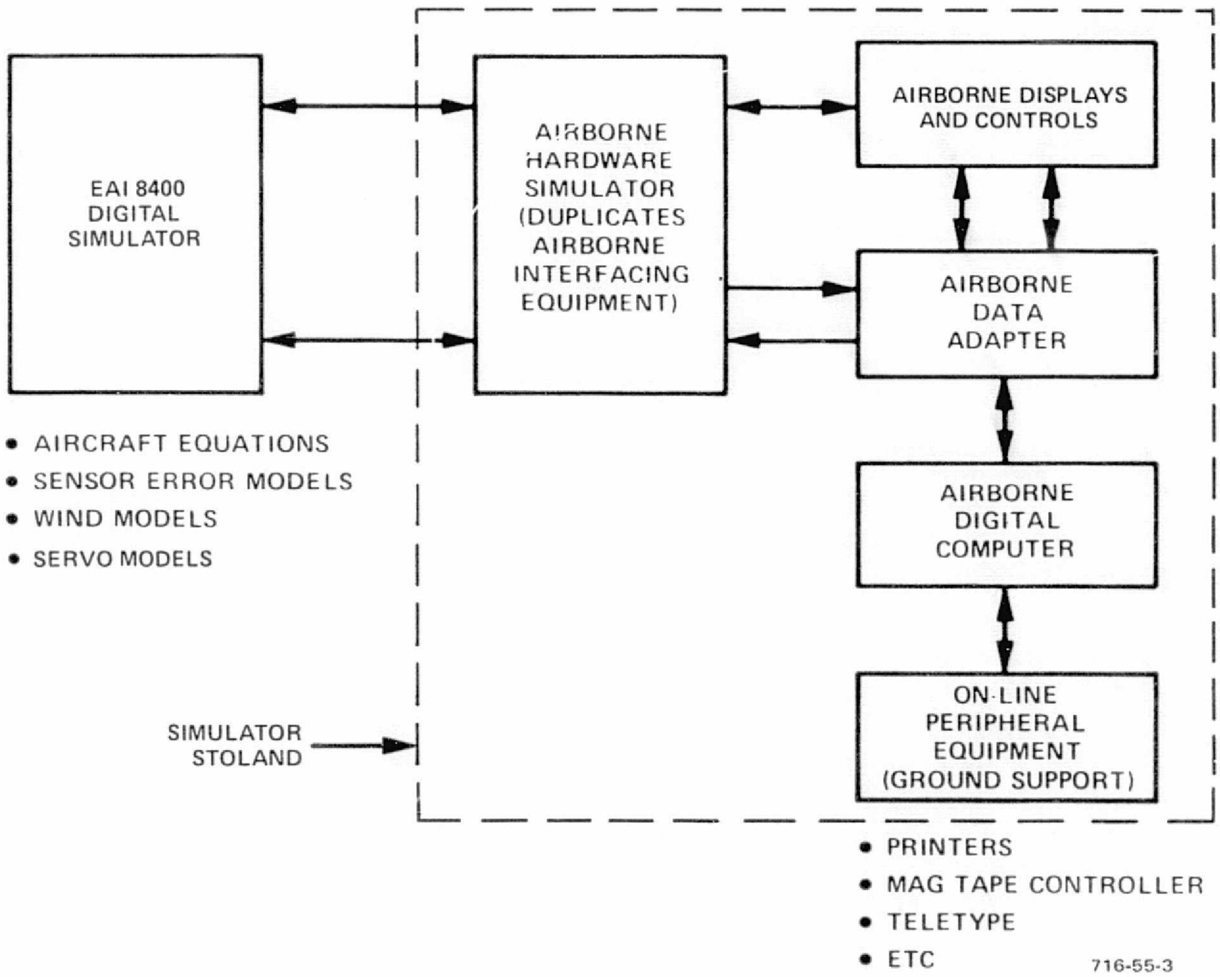

Figure 4-1
Validation Facility

The key to the validation facility is the Airborne hardware Simulator (AHS). The AHS communicates with the simulation computer via a custom interface that is tailored to the EAI 8400 computer used for the simulator. Flowing from the simulator to the AHS is the aircraft state information that would be measured by the various airborne sensors (accelerations, angular rates, attitude, heading, bearing and distance to reference points, static and differential pressures, outside air temperature, etc). Transmitted with this information are error models, when required, such as superimposed noise of the appropriate statistical and spectral characteristics associated with the sensor that measures that information.

The AHS then processes this information so that the electrical static and dynamic characteristics of the specific airborne sensor is exactly duplicated. For example, distance is measured and transmitted by the DME receiver which outputs its data in the ARINC 561 serial digital format. The AHS function involves the following signal processing. The distance number from the simulator is transferred via a digital-to-digital interface to the AHS at the computation rate of the simulator. The distance data is steered to a particular buffer memory address in the AHS. An ARINC 561 serial digital transmitter representing the receiver output state is mechanized in the AHS. This transmitter's control acquires the required digital DME word from the AHS buffer memory at the proper timing interval and outputs the data through an electrical interface identical to the one that exists in the DME receiver in the aircraft.

Flowing from the airborne Data Adapter to the digital simulation via the AHS are the servo command signals to the STOLAND servo actuators which are modelled in the EAI 8400 simulation. It would have been preferable to feed these signals via the airborne Servo Interlock Unit which could drive airborne actuators in the simulator cockpit cab. This is an expensive alternative that is normally only provided when a full "iron bird" simulation facility is available.

The AHS also contains a special digital-to-digital interface which permits direct data transfer between the 1819A airborne computer and the EAI 8400 simulation computer. This interface is used to synchronize the initialization of the airborne computer with the initialization of the simulation computer.

In addition to the AHS, the validation facility contains a system bench for interconnection of all elements of the airborne system. This bench provides a center for distribution of data to and from the AHS, airborne equipment, simulation computer and the simulation cockpit.

Finally, the validation facility contains all of the necessary peripheral equipment and support software needed for software development.

Figure 4-2 is a photograph of Simulator STOLAND as delivered to NASA about one year after program go-ahead. It is installed in one of NASA/ARC's simulation laboratories. The large bench at the upper left is the simulator system equipment rack. It contains the rack-mounted airborne equipment and associated wiring and is interchangeable with the Flight System Equipment Rack. (In the figure, two of the LRUs were not installed at the time the photograph was taken.)

Immediately adjacent to the bench is the Airborne Hardware Simulator.

At the right is the 1819A Peripheral Controller. It includes a paper tape punch and reader and the interface equipment for operating with a teletype, CRT terminal, magnetic tape controller, line printer and card reader. The latter two items are standard items in the NASA simulation laboratory and are located a few feet to the right of the photograph.

CRT terminals have now replaced the teletype, and magnetic tape has replaced the paper tape.

716-55-37

Figure 4-2
STOLAND Validation Facility Delivered to NASA

C. SOFTWARE DEVELOPMENT FACILITIES

The complement of peripheral equipment used during the development and validation phases of the program is shown in Figure 4-3. A peripheral controller interfaces with the computer I/O. That controller contains the I/O drivers, receivers and control logic to interface with the 1819A. It also contains the drivers and receivers that allow communications with:

- Teletype
- CRT terminal
- Paper tape reader
- Paper tape punch
- Line printer
- Magnetic tape controller and transport

Software development is done at Sperry and NASA using magnetic tape. The source programs and object tapes (machine language programs) are on magnetic tape. The object tapes are also generated on paper tape.

The 1819A computer shown in the figure contains all of the software needed to operate on-line with all of the peripheral equipment shown.

Minor program changes are made via the teletype keyboard or CRT terminal that operates in an interactive mode controlled by the utility program, which remains core-resident in the computer's memory. The capabilities of the utility program were discussed in Paragraph III.B.13.b.

D. STOLAND AUTOMATIC TEST EQUIPMENT

Figure 4-4 is a photograph showing the ATE installed at NASA/Ames Research Center. This equipment is the 1972 version of Sperry's standard ATE product. Suspect airborne equipment is tested on the ATE to verify failure. After repair, the LRU is tested on the ATE to its component test specification. The ATE provides printed records of the LRU's performance in the test against each item of the component test specification.

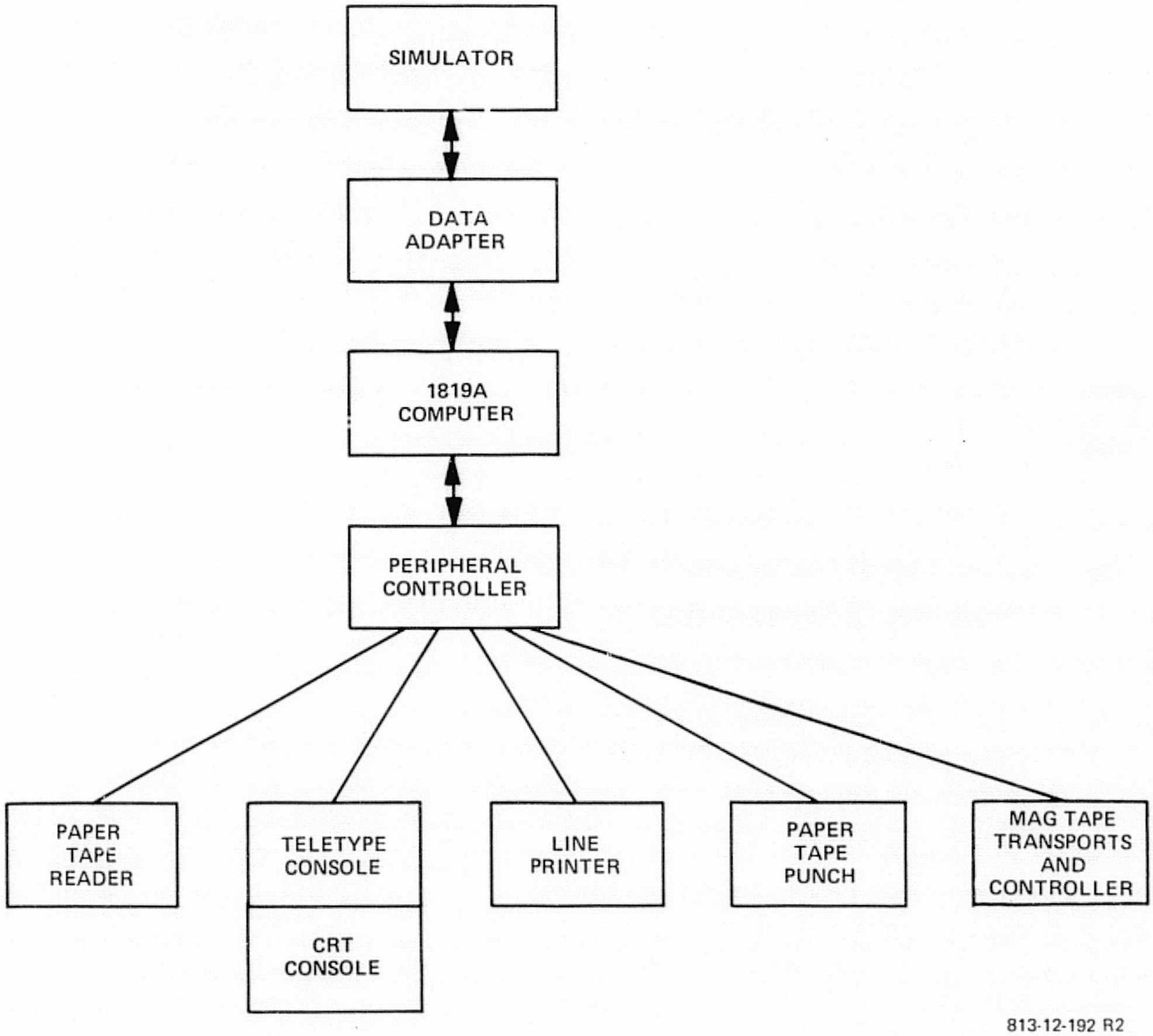

Figure 4-3
Software Development Facilities

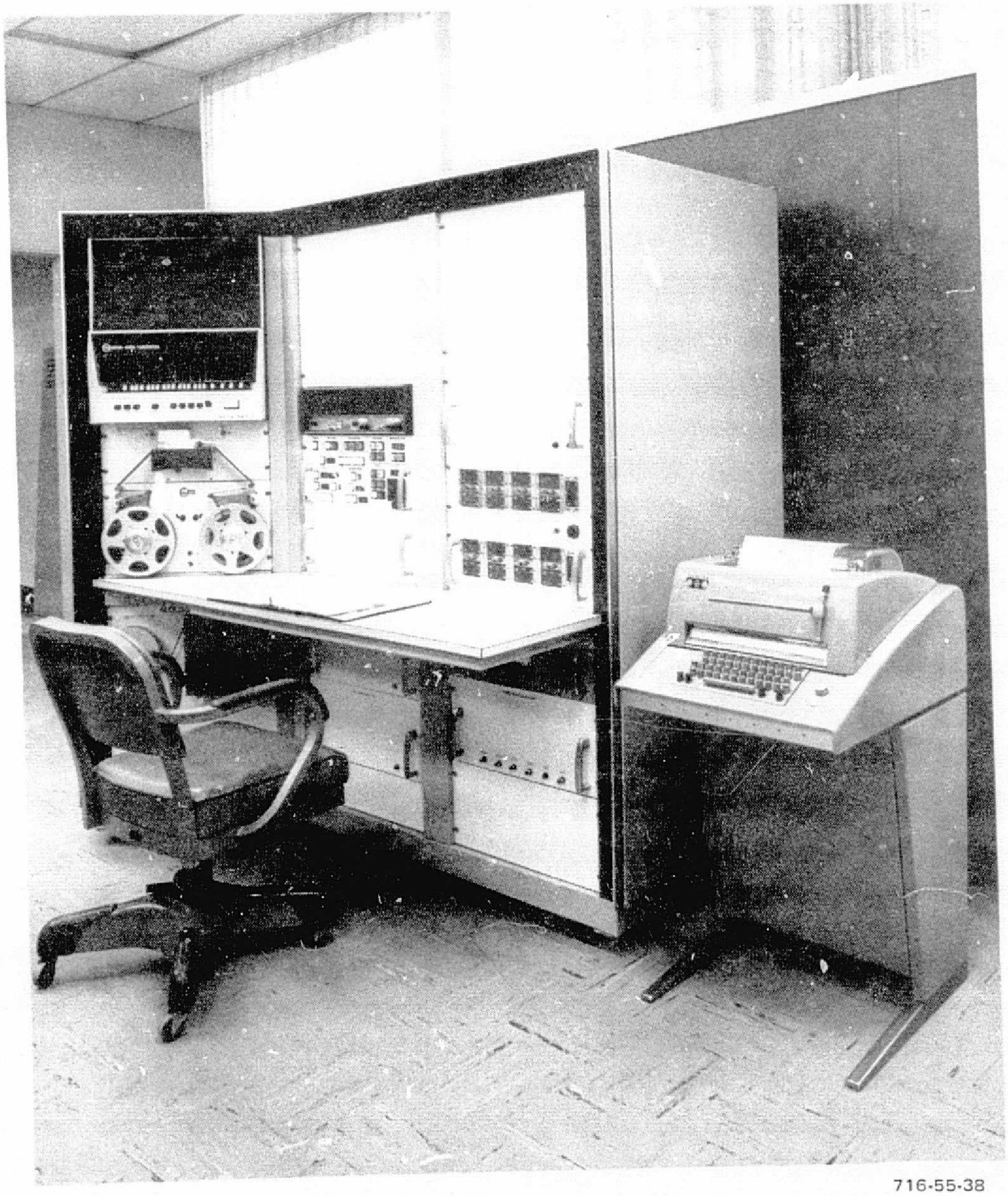

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Figure 4-4
STOLAND Automatic Test Equipment (ATE)

Automatic test program tapes have been developed and delivered by Sperry for testing of the following LRUs.

- Pitch Rate Gyro
- Roll Rate Gyro
- Yaw Rate Gyro
- Normal Accelerometer
- Lateral Accelerometer
- Longitudinal Accelerometer
- Panel Power Supply
- Mode Select Panel
- Status Panel
- Keyboard
- Multifunction Display MFD
- MFD Symbol Generator
- MFD Controller
- Electronics Attitude Director Indicator (EADI)
- EADI Symbol Generator
- RD-202 HSI
- HSI Amplifier Rack
- HSI Signal conditioning Unit
- DDAS Instrumentation Unit
- Servo Interlock Unit

E. STATIC ACCEPTANCE TESTING

Static acceptance tests were conducted at Sperry on both sets of flight equipment. For these tests, all the hardware in Flight STOLAND was interconnected, using the actual prefabricated airborne cable harnesses and connectors. The tests verified every analog, digital and discrete interface in the system, and in particular, the accuracy of all analog interfaces was specified statically from end to end and verified.

The configuration of the equipment for the test is shown in Figure 4-5.

The testing was done in three sections. In the first section, all interfaces to the cockpit displays and control panels were checked using the STOLAND automatic preflight test. This part of the test therefore also verified the preflight test software associated with the displays and panels.

For the second section, the Data Adapter signal inputs and outputs were jumpered to an Airborne Hardware Simulator as shown by the solid lines at the jumper interface in Figure 4-5. Signals transmitted from the 1819A computer in the TEST EQUIPMENT were then verified to be received properly scaled and

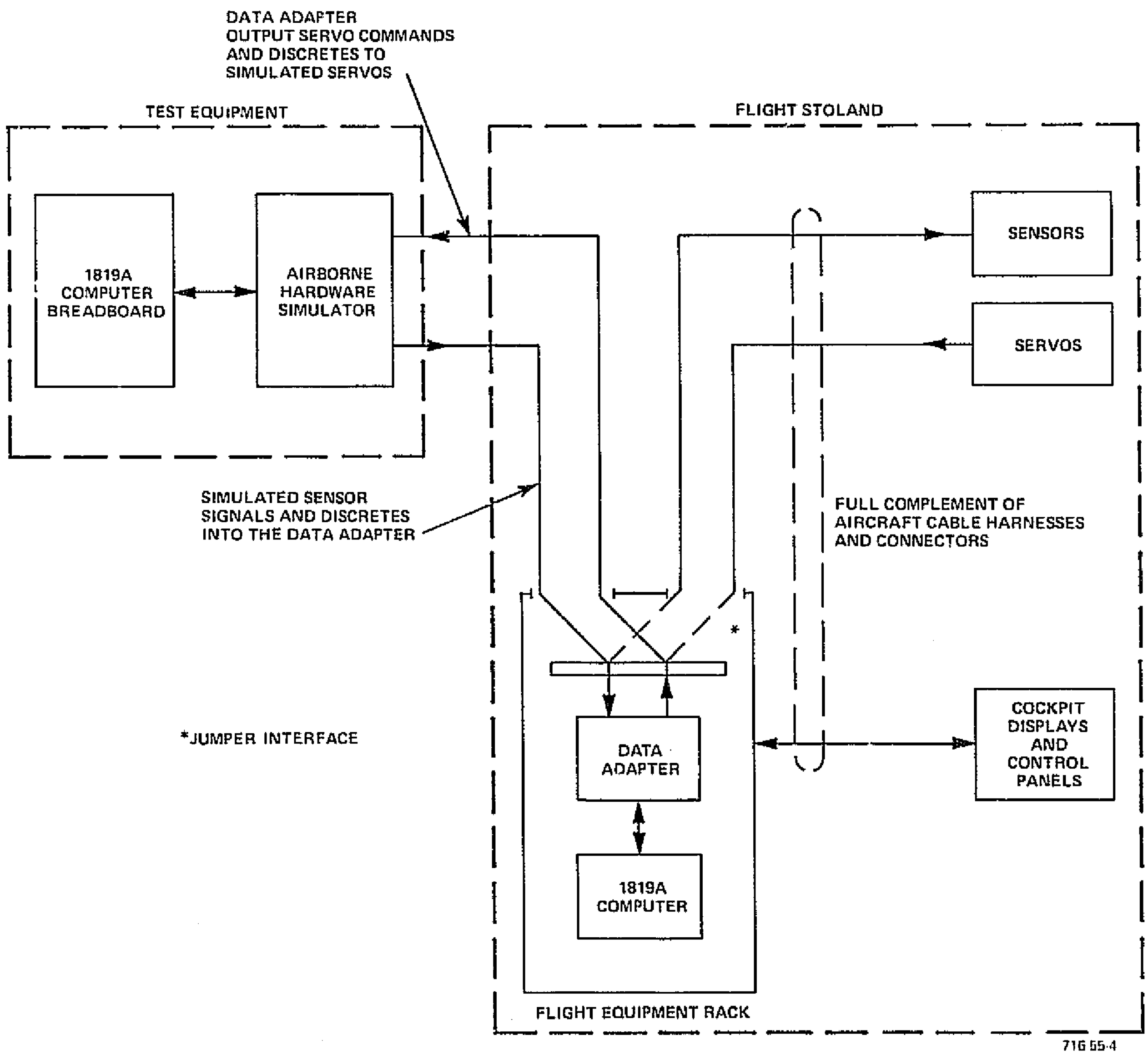


Figure 4-5
STOLAND Static Acceptance Test Configuration

sensed in the buffers of the airborne 1819A. Similarly, signals from the airborne computer were verified to be received properly, scaled and sensed in the buffers of the TEST EQUIPMENT computer.

For the third section of the test, the jumpers were connected as shown by the dotted lines so that the system was then wired exactly as it would be in the aircraft. The sensors were exercised and the proper response in the 1819A airborne computer and on the cockpit displays verified. Similarly, the airborne computer was programmed to output specific servo commands and the proper response at the system servos was verified.

The following points about the Static Acceptance Tests are noteworthy:

- The tests included checkout of the actual flight cable harnesses and connectors as well as the flight equipment.
- The Airborne Hardware Simulator, which is an important part of Simulator STOLAND was intrinsically tested during the test.
- The tests demonstrated that the Flight Equipment Rack may be used for ground simulation as well as for flight.

F. DYNAMIC ACCEPTANCE TESTING (DAT)

The formal Dynamic Acceptance Testing of the hardware and software as a complete system on the validation facility at NASA/Ames represented important milestones in the STOLAND program. In all, four separate dynamic acceptance tests were conducted, each with full pilot participation. The testing was extensive, covering a period of several days in each case. The first DAT was on the Simulator STOLAND set of equipment software in December 1972. This was followed in January 1973 by the DAT of the first set of flight equipment. At that time, the NASA simulation computer contained a C8-A airplane simulation and so the 1819A software for both tests was configured for the C-8A. Later, NASA replaced the unmodified Buffalo (C-8A) simulation with the Augmentor Wing. Sperry then developed the 1819A software for the Augmentor Wing. The DAT of this system was completed in September 1973. Software for the Twin Otter was developed during 1973/1974 and the final DAT, for the Twin Otter, was run in June 1974.

Each of the tests followed a similar procedure, which is outlined later.

For the majority of the tests, acceptance was based on the pilot's opinion of system behavior as observed o. the simulator cockpit instruments and control panels. For some tests, performance numbers were specified in the test procedure document. Data was recorded on the STOLAND magnetic tape unit for all the tests.

The test procedure was, essentially, divided into five sections which are explained below.

<u>Section 1</u> - This section contained a dynamic checkout of the basic modes and interlocks in the system. Basic modes and interlocks as used here means all those modes that will be found in a modern conventional air transport type of flight control system. These modes included pitch control wheel steering, pitch attitude hold, flight path angle hold and select and indicated airspeed hold and select. In the lateral axes they covered roll control wheel steering, roll attitude hold, heading hold and select and turn rate hold and select. The autothrottle indicated airspeed hold and select modes were also covered. In addition, conventional use of the VOR, DME, TACAN and approach navigation aids was contained in this section of the test.

<u>Section II</u> - This covered tests to demonstrate the performance of the system when coupled to reference flight paths. This included coupling to a flight path, 3D and 4D guidance and approach to touchdown in semi-automatic and fully automatic (FULL-AUTO) modes. In addition, the ability to change the flight path in flight was demonstrated.

<u>Section III</u> - Contained quantitative tests on the performance of the basic modes. In these tests the response of the system to pilot-injected changes and pulse wind disturbances was verified. The transient response of the sytem was recorded and verified to be within acceptable limits defined in the test procedure document. The responses covered longitudinal stabilization, lateral directional stabilization - at high and low speeds - horizontal and vertical flight path control and speed control at high and low speed, including automatic configuration changes from high to low speed and vice versa.

Section IV consisted of a series of data runs in which the system was coupled to different flight paths and flown through to touchdown. Runs were made in the automatic, fully automatic and flight director modes using TACAN, VOR and MODILS navaids. Baseline runs were repeated with a variety of navaid error models and with different mean wind profiles and random wind models.

Section V was made up of a set of off-nominal tests. In these tests simulated failures of the system were injected during critical phases of flight - usually on final approach or during automatic flare. For each failure case, the ability of the system's automatic monitors to disengage the system was recorded and the pilot's ability to recover from the failure situation was noted. The resulting data provided a basis for not having to repeat many of these system failure checks during the flight testing that was to follow.

G. FLIGHT TESTING

The STOLAND system was flight tested on three aircraft, the CV340, the Augmentor Wing and the Twin Otter.

1. CV340 Flight Testing

A series of eight preliminary shakedown flight tests on the CV340 were made in May, June and July 1973 following the simulation dynamic acceptance testing of the first set of flight equipment and software. The software was in fact configured for the unmodified Buffalo (C8-A) at that time, but this did not significantly affect the flight testing because no control servos were installed and the objective was to check out the flight director and basic instrumentation and displays in a flight environment. The system proved to be compatible with the aircraft and overall the hardware and software worked well in flight. The low frequency noise on the signals from the VOR and TACAN receivers was somewhat larger than that simulated during the dynamic acceptance testing and so the VOR and TACAN radial capture and track control laws were revised to accommodate these signals.

Following these preliminary shakedown flights in the CV340, NASA personnel conducted a series of flight experiments to investigate the accuracy of the 3D and 4D terminal area guidance concepts used in STOLAND. These experiments are reported in Reference 5.

2. <u>Augmentor Wing Flight Testing</u>

The first flight tests on the Augmentor Wing were made in November and December 1973. The full complement of STOLAND equipment was installed, including all the control surface servos and actuators and the nozzle and throttle servos, making eleven controlled mechanisms in all. Five flights were made all together, the objective being to get a preliminary look at any aircraft interface compatibility problems prior to the main flight testing which was to follow in late 1974. These preliminary tests were most successful. Almost all the hardware operated satisfactorily and the basic control modes including control wheel steering were well exercised at high and low speeds. The flights demonstrated that some adverse yaw problems existed in roll control wheel steering, particularly at low speeds. This was corrected for the later flights. Also, dropouts of the raw navigation data without loss of valids were a nuisance and appeared to upset the navigation complementary filters. The pilots felt that the control forces required to override the flap servo were excessive and that the Servo Select Panel, which was located on the Flight Equipment Rack should be relocated in the cockpit so that they could make servo selections in flight. These problem areas were corrected for the main series of flight tests which followed in late 1974.

During 1974, changes to the Augmentor Wing speed control philosophy resulted in extensive software modifications that were incorporated and checked out in the validation facility. In addition, longitudinal control of the airplane was changed so that in the low speed STOL mode configuration, (flaps greater than 45 degrees) airspeed would be controlled using the elevator and flight path controlled by changing the thrust. The speed control changes included thrust and speed limiting to ensure that aircraft maneuver margin could not decrease below acceptable minimums in all flight conditions. These minimums were set at .4g in the STOL mode and .6g in the non-STOL mode. A throttle flight director was added for use in the STOL Mode.

Earlier flight tests had indicated excessive backlash in the airframe engine controls. This backlash could introduce serious limit cycle problems in the autothrottle outer control loop and so the autothrottle software was modified to control engine rpm directly using engine rpm sensors provided by NASA. These sensors also permitted direct software control of the minimum thrust for the maneuver margin control mentioned above and they permitted software control of the maximum permissible engine speeds.

Before Augmentor Wing flight tests were resumed, Sperry added additional hardware to permit control of the wing flap chokes via STOLAND.

Flight testing was resumed in November 1974. From this point on, two independent sets of flight tests were conducted using STOLAND. The system was being used by NASA using a special set of research software in a handling qualities research study. This research included the use of the wing flap chokes for direct lift control. The Sperry-developed software was also tested through to fully automatic 4D reference flight path control and automatic landings. The Wing Flap chokes were not used for any of these tests. A brief description of these latter flight tests follows.

These tests consisted of a series of 22 flights between November 1974 and September 1976. The test sequence was as follows:

- Initial shakedown flights to verify that basic system performance was the same as in December 1973 and that the adverse yaw problems in CWS turns had been solved.

- Aircraft calibration runs. From the December 1973 flights it appeared that the aircraft trim conditions were not exactly the same as on the simulator. In these flights the power required to make 4-degree flight path angle climbs and descents in the cruise configuration and 7.5 and 4.1-degree descents in the STOL configuration, and at different weights for each flight path angle, was measured. These flights were important because STOLAND is

configured to limit the minimum and maximum engine rpms to maintain maneuver margin and not overstress the propulsion systems. The nominal engine rpm setting must lie well in between these limits to maintain a sufficient control margin.

- Cruise flight hardover tests on the pitch, roll and yaw series and parallel servos. For these tests the automatic servo monitoring was disabled and the tests were made with the pilot's hands both on and off the controls.

- Automatic flares at Crows Landing with the system altitude biased in the software to make the aircraft "touchdown" 300 feet above the runway. These flares were made to increase pilot confidence in the system prior to going to the ground and to get a preliminary look at some flare characteristics. As a result of these flares, the elevator parallel servo authority was increased.

- Flight testing of the increased authority elevator servo. This included hardovers and authority measurements in the cruise and approach configurations and the injection of nose down hardovers during the flare maneuver at close to 300 feet radio altitude.

- Automatic flares to the ground at Crows Landing, starting with -4.1 degree approach glideslopes. These approaches were made with the system initially in altitude hold and heading hold, capturing the MLS localizer at various angles from zero to 90 degrees on the base leg.

- Automatic flares from -7.5-degree glideslopes, starting from altitude and heading hold.

- Automatic guidance and control on a 4D reference flight path, followed by automatic approach, flare and decrab.

During these tests, noise and dropouts on the raw bearing data from the VOR and TACAN equipment became a problem, particularly when the system was navigating between Moffett Field and Crows Landing. This problem was solved in the software by incorporating "invalid data detectors" which, upon being tripped, automatically cause the system to use dead reckoning navigation (based on inertial estimates without the use of ground aids) until the raw data recovers.

Two other problems were also dominant. Firstly, the throttle glide path holding mode was lightly damped with a period of about 12 seconds. This light damping was more noticeable on the glideslope during the early part of the approach. Secondly, the flare performance was not consistent. Neither of these problems exist on the validation facility. They are discussed in more detail in Section V, Contractor Observations and Recommendations.

3. Twin Otter Flight Testing

Flight testing of STOLAND in the Twin Otter started in October 1975 and ended in December. The Twin Otter is a much simpler aircraft than the Augmentor Wing and so the tests progressed rapidly through to automatic landing. The test sequence was very similar to that on the Augmentor Wing and is indicated below.

- Initial shakedown flights to verify basic mode performance and iron out any aircraft compatibility problems.

- Cruise and approach flight condition hardover tests on the pitch, roll and yaw servos. These tests were made with and without the automatic monitoring and with and without pilot intervention. The elevator servo was changed to increase its authority. This was required for automatic flare and to ensure that it could handle the large pitching moment change when the flaps are initially lowered.

- Automatic flares to 300 feet at Crows Landing, including nose down hardovers during the flare.

- Automatic flares to the ground with decrab.

- Automatic guidance and control on a 4D reference flight path, followed by automatic approach, flare and decrab.

In these flights, two significant problems that are equally applicable to the Augmentor Wing were identified. The first problem was associated with relatively large pitch and roll activity on the localizer and glideslope when the aircraft was more than 3 miles or so from touchdown. This activity was due to noise on the MLS localizer and glideslope signals and was minimized by gain scheduling the glideslope and localizer error signals inversely proportional to range. The second problem caused relatively large overshoots (300 to 400 feet) off the localizer during localizer capture at angles approaching 90 degrees. This overshoot is not normally a problem, but on a STOL aircraft making intercepts at only 2 miles to touchdown, it does not allow much time for the aircraft to stabilize on the localizer. The overshoot was caused by errors in the inertial sensors due to the rapid turning maneuvers and aircraft decelerations from cruise to STOL speeds as the airplane turned from the downwind leg onto the base leg and then onto the approach localizer. This problem was solved by increasing the gains in the navigation complimentary filters so that when MODILS navigation was in use, the complement would be weighted more heavily to use raw navaid data as compared to inertial data.

A third problem, peculiar to the Twin Otter, was also observed. With the aircraft initially established on the localizer centerline, it would be temporarily disturbed off the localizer following glideslope capture. This problem was caused by the power reduction for glideslope capture. The power reduction was not equal for both engines, resulting in a significant directional trim change. This problem was solved by pilot technique. During glideslope capture, the pilot would rebalance the engine torque pressures at the throttle levers using the cockpit torque pressure gauges.

H. TYPICAL TEST DATA RUNS

In this section, some typical data runs are described for the Augmentor Wing and the Twin Otter. Data is shown both for simulator runs and flight test runs for purposes of comparison.

The data presented shows the behavior of the Augmentor Wing and Twin Otter systems on the simulator in the fully automatic modes for an automatic localizer capture in altitude hold, followed by automatic configuration change and speed reduction, through to glideslope capture and track. This is followed by an automatic flare and landing. This data represents considerable automatic control activity both laterally and longitudinally.

For each system, one set of data shows details of the final glideslope track and flare maneuvers for both the simulator and in flight. For these runs, an attempt was made to duplicate on the simulator the conditions that occurred in flight so that the simulator performance and airplane performance can be compared.

All of the above data was reduced using the STOLAND magnetic tape data reduction facility. Both inflight and on the simulator, data was recorded digitally using the STOLAND magnetic tape transport and later reduced into the strip charts shown. In each case, the top channel shows a real time code in pulse form. Each group of six pulses is read right to left, the first pair of pulses representing hours, the second pair minutes and the third pair seconds. The actual time is marked by the leading (furthest left) edge of the unit's seconds pulse. Except for the integer zero, the amplitude of each pulse is proportional to the integer (1 through 9) being represented. For example, the integer 4 is represented by a pulse of four large divisions (20 small divisions). The integer zero is represented by a half large division pulse (2-1/2 small divisions).

1. Typical Augmentor Wing Approach and Landing

a. Localizer Performance

Figures 4-6, 4-7, 4-8 and 4-9 show lateral directional and longitudinal simulator data for an 80-degree localizer intercept with the aircraft in a clean configuration at 130 knots in altitude hold and autothrottle airspeed hold. Range to touchdown was approximately 6 miles. From Figure 4-6, the capture is initiated at 02:40:58 with a left wheel command into a 30-degree LWD turn followed by rollout onto the localizer. The localizer overshoot is 400 feet and is considerably smaller than this for smaller intercept angles. Figure 4-7 shows the body axis lateral acceleration during the roll into and out of the turn to not exceed .025g and is approximately zero during the turn. Figure 4-8 shows the elevator and thrust changes (NH) required during the turn to maintain altitude and airspeed. The data shows airspeed remaining constant at 130 knots. Figure 4-9 shows the altitude remaining constant at 1440 feet.

b. Automatic Speed Reduction and Configuration Change

At 02:41:40, immediately following localizer capture, the pilot selected FULL AUTO at the Mode Select Panel. Figures 4-8 and 4-9 show the automatic speed reduction to 77 knots and the automatic flap deployment to 65 degrees resulting from this selection. Note from the altitude trace in Figure 4-9 that the altitude did not balloon by more than 35 feet during this maneuver and that the attitude and altitude rate traces on Figure 4-8 indicate very mild transients. As the flaps pass through 45 degrees during the deceleration, STOLAND automatically transitions into the STOL mode where it controls speed with elevator and vertical flight path with thrust. The small transients in the Figure 4-8 traces (around time 02:42:20) are caused by this transition. Note the smoothness of the speed transition and minimal speed undershoot in Figure 4-8 as the airspeed settles onto 77 knots. An automatic power addition to 98.4 percent NH is required to hold the aircraft at 77 knots at constant altitude with the flaps fully deployed.

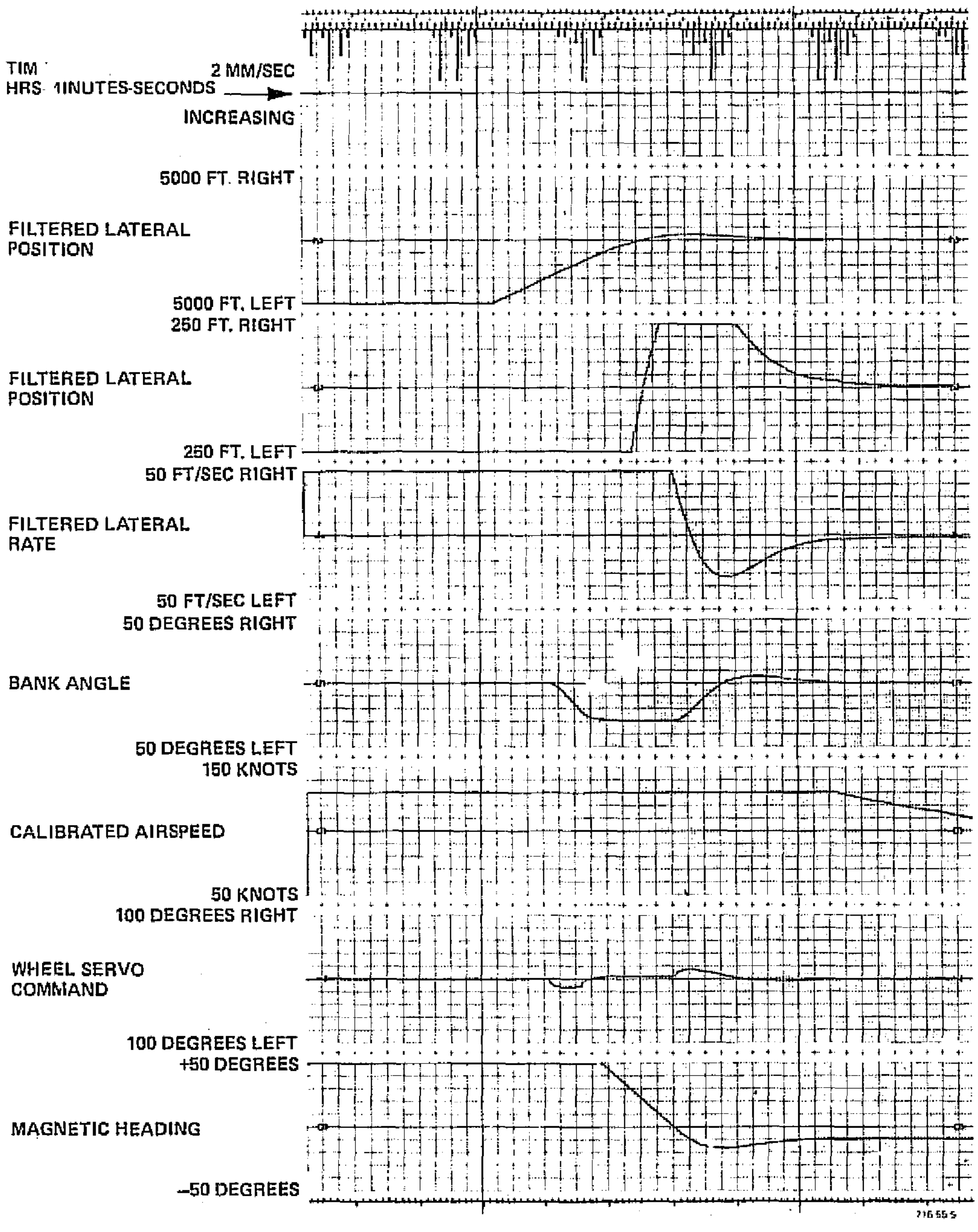


Figure 4-6
Localizer Capture, Augmentor Wing Simulator Run -
Lateral Directional Data

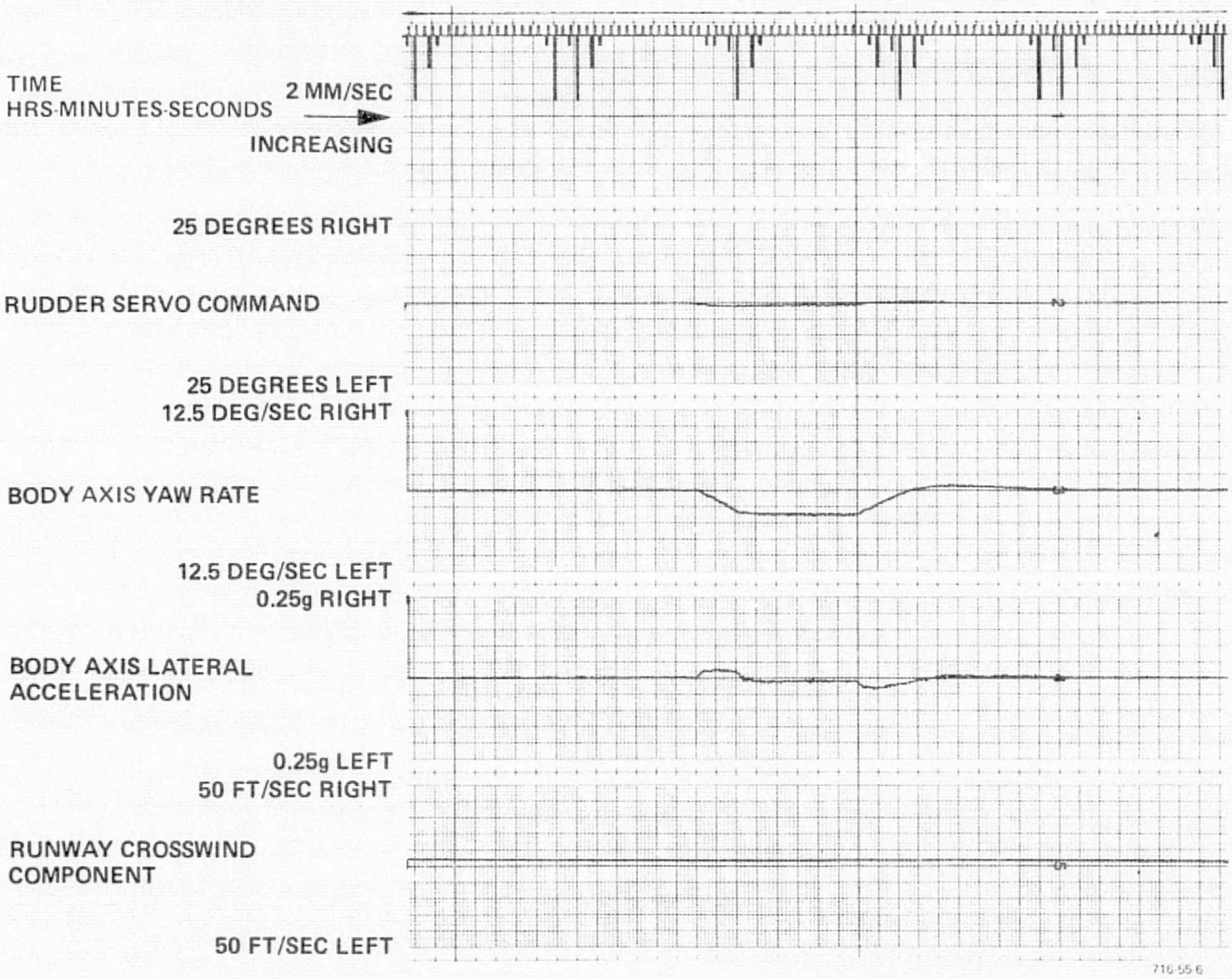


Figure 4-7
Localizer Capture, Augmentor Wing Simulator Run,
Lateral Directional Data

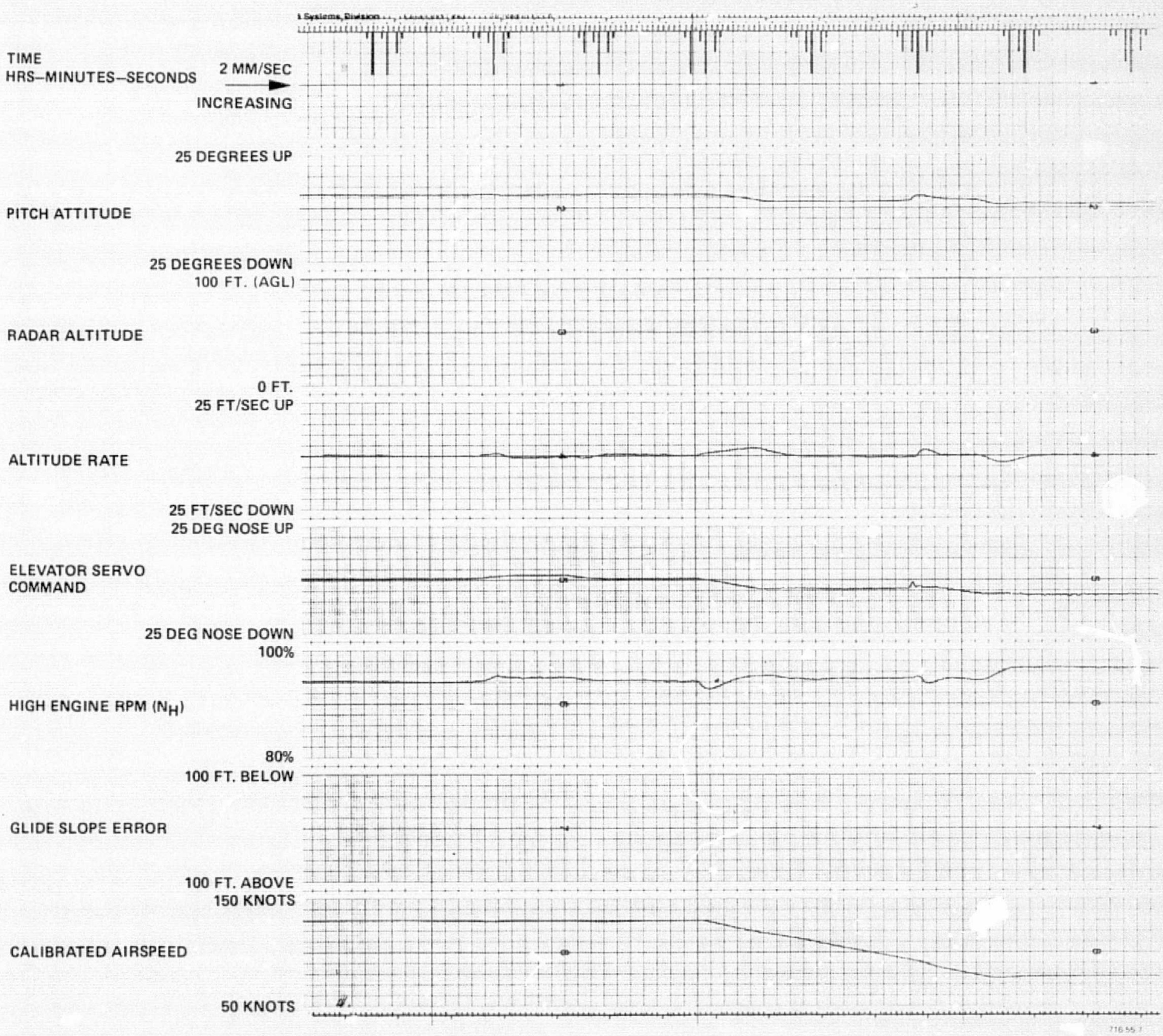


Figure 4-8
Automatic Configuration Change and Speed Reduction, Augmentor Wing Simulator Run, Longitudinal/Vertical Data

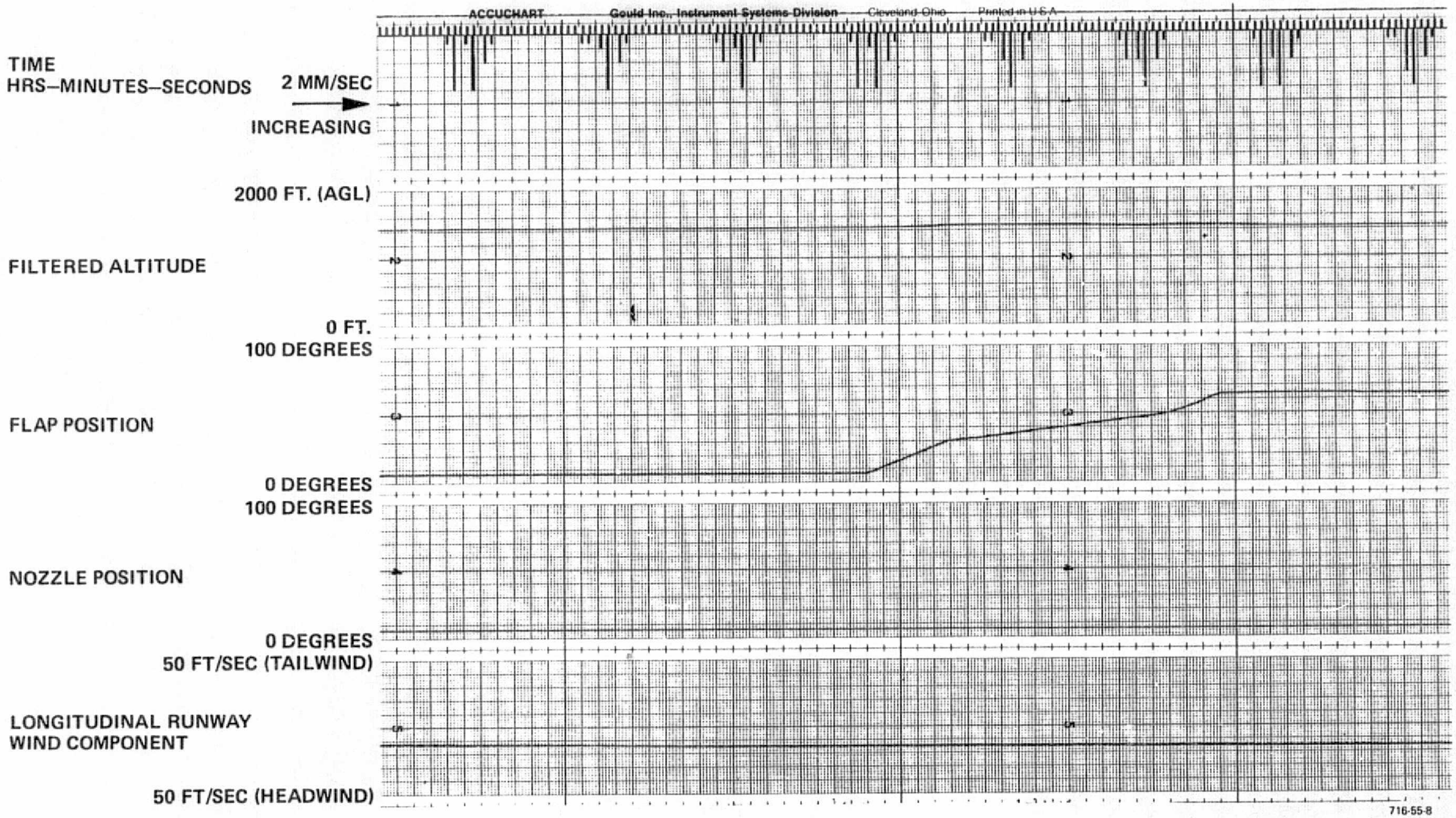


Figure 4-9
Automatic Configuration Change and Speed Reduction, Augmentor Wing Simulator Run, Longitudinal/Vertical Data

C-2

c. Glideslope Capture/Track and Flare

Glideslope Capture/Track and Flare have been areas of difficulty in control of the Augmentor Wing aircraft. Performance in these areas will be illustrated with a comparison of simulator and flight data. Glideslope and Flare performance in the simulator has generally been good. However, in flight, the glideslope tracking mode has been characterized by a lightly damped flight path angle mode with a period of about 12 seconds (although the path is held within 25 feet). Also, the flare has demonstrated less consistency in flight than in the simulator with a general tendency to float. These problem areas are discussed in detail in Section V, Observations and Recommendations.

Good simulator Glideslope Capture/Track and Flare performance is demonstrated in Figures 4-10 and 4-11. This simulator run was made with conditions duplicating, except for turbulence, conditions which were present for the flight data presented in Figures 4-12 and 4-13. Note, however, that only the final portion of the glideslope capture maneuver is shown in Figures 4-12 and 4-13.

For the simulator run, glideslope capture is initiated at 02:44:37 as shown on Figure 4-11 when the nozzles start lowering toward 70 degrees. The glideslope error trace in Figure 4-10 shows a smooth transition of flight path onto the glideslope. The discontinuity in this trace at 02:44:50 is caused by a scaling change with the system switching into glideslope track control. The ±100-foot scaling of the error signal is correct from this point onward. The data shows the overshoot above the glideslope to be less than 20 feet. During the capture STOLAND automatically allows and controls the airspeed to reduce to the final approach speed of 68 knots as shown in Figure 4-10. This simulated approach was made with a 10-knot headwind on a -7.5 degree glideslope. The STOLAND computed wind is shown on Figure 4-11 to be approximately 17.5 feet per second or 10.4 knots.

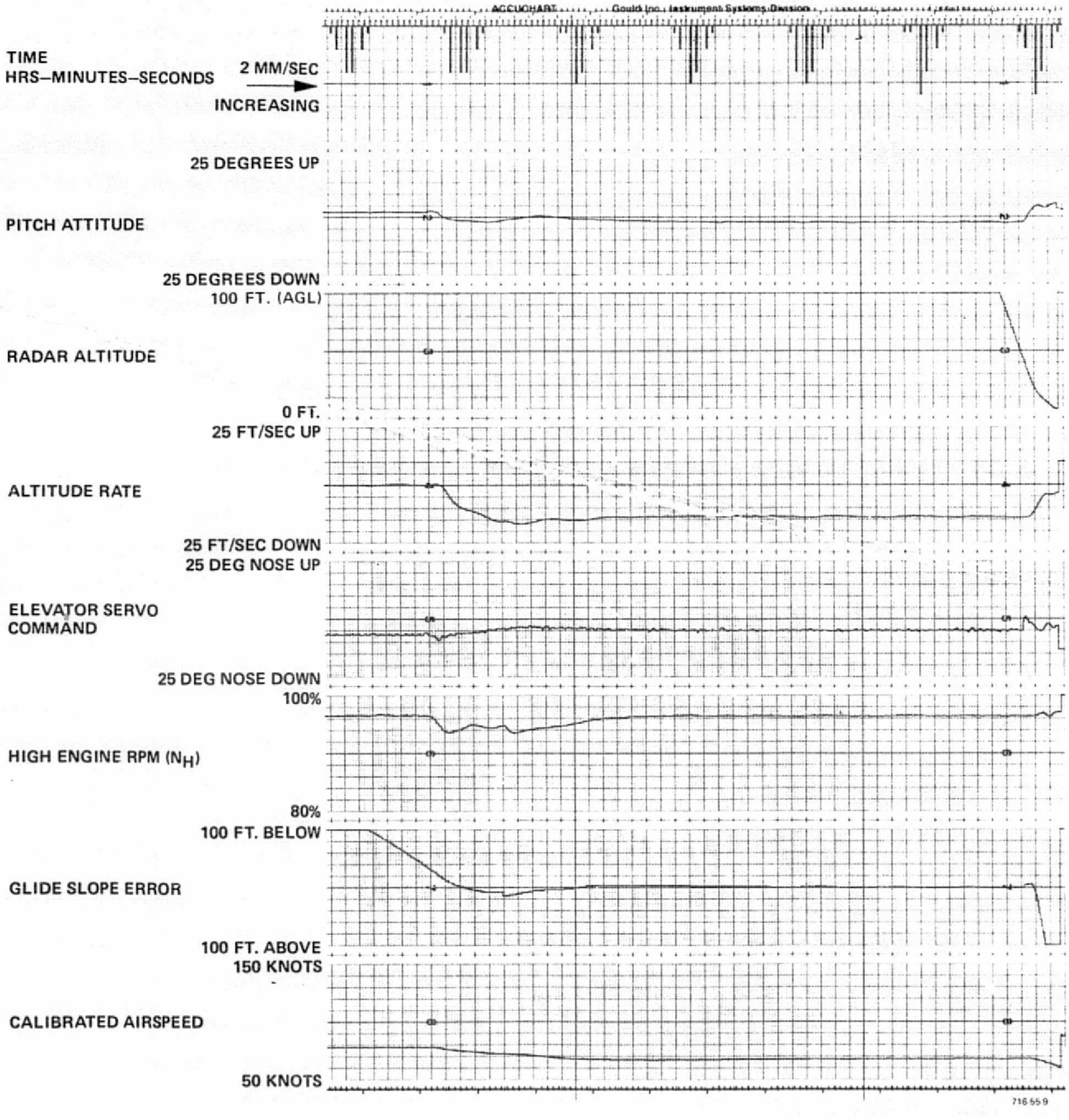


Figure 4-10
Glideslope Capture/Track and Flare, Augmentor Wing Simulator Run,
Longitudinal/Vertical Data

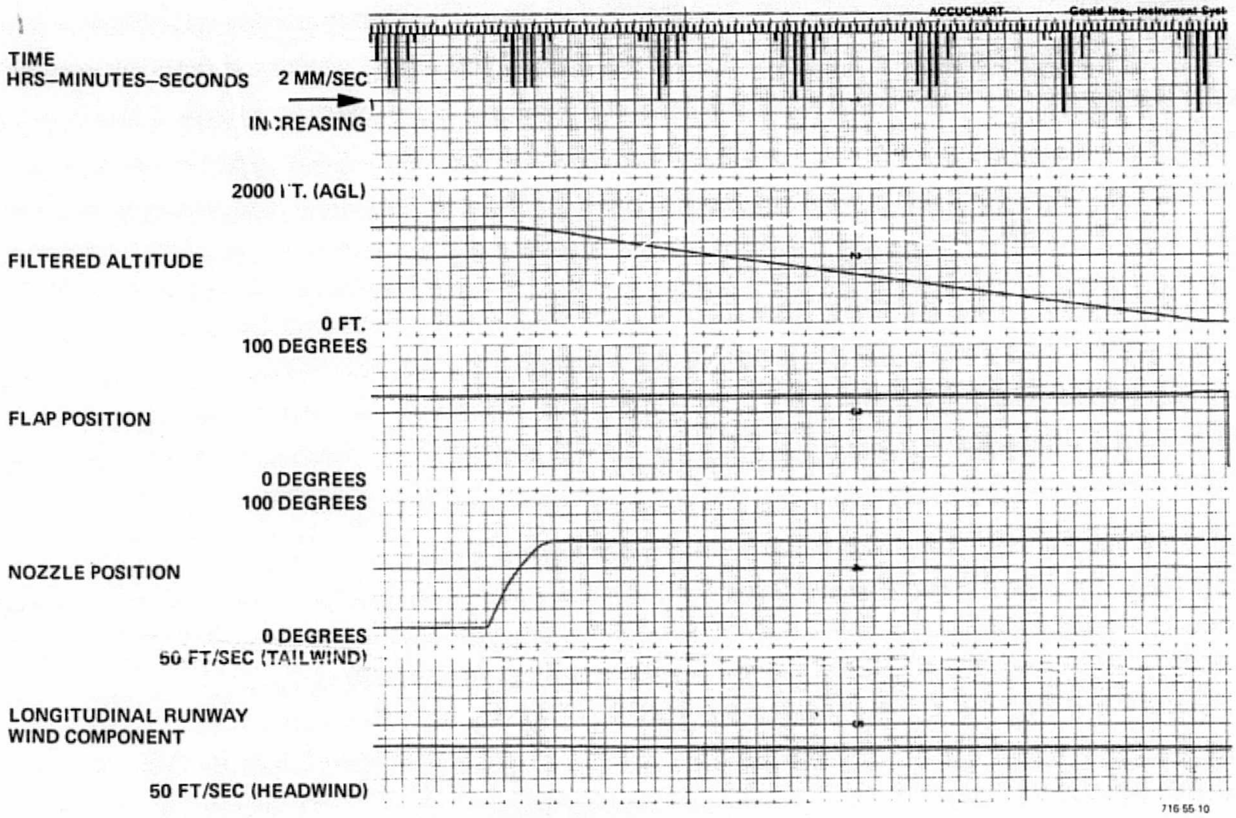


Figure 4-11
Glideslope Capture/Track and Flare, Augmentor Wing Simulator Run,
Longitudinal/Vertical Data

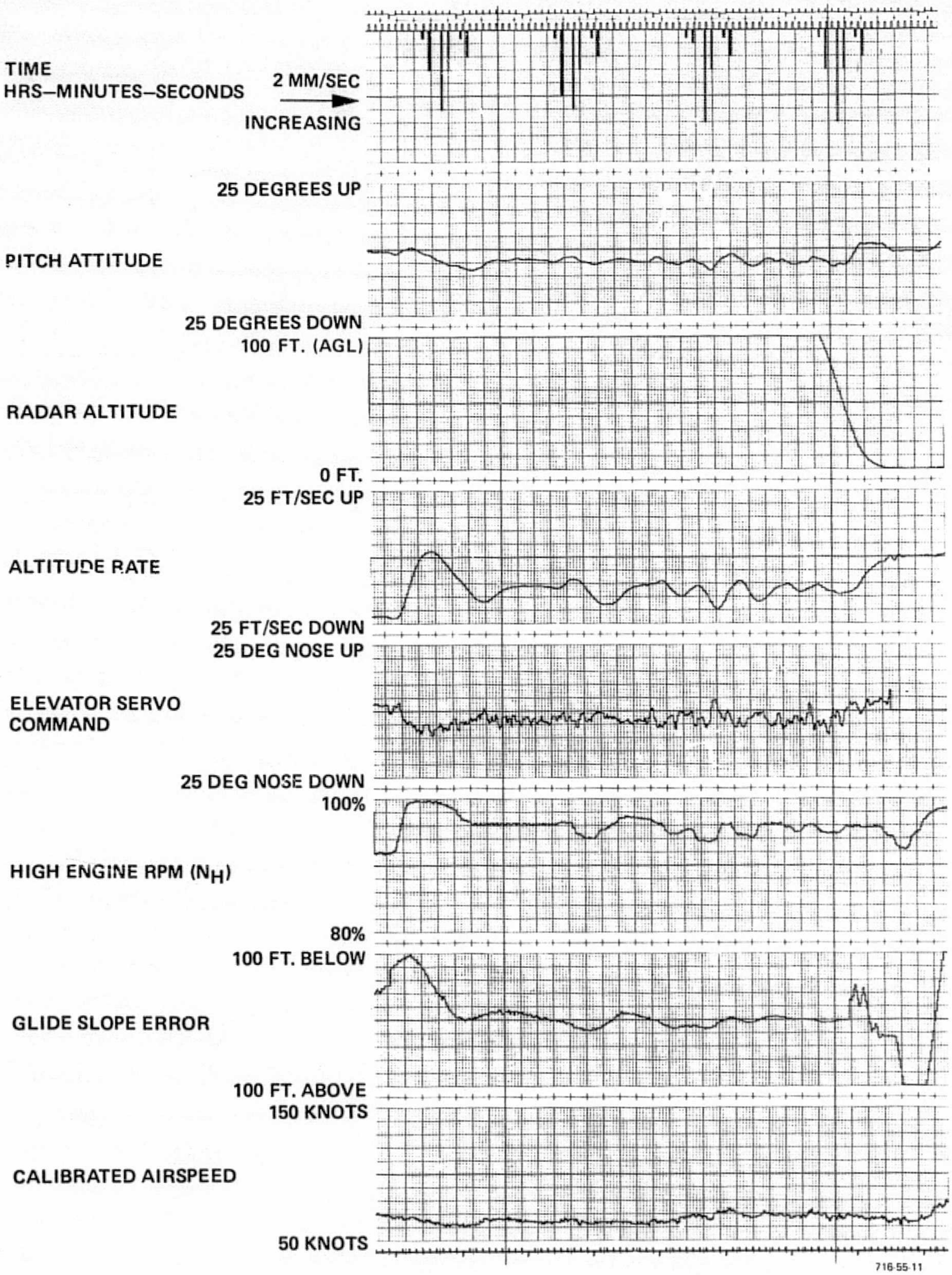


Figure 4-12
Glideslope Track and Flare, Augmentor Wing Flight Data,
Longitudinal/Vertical Data

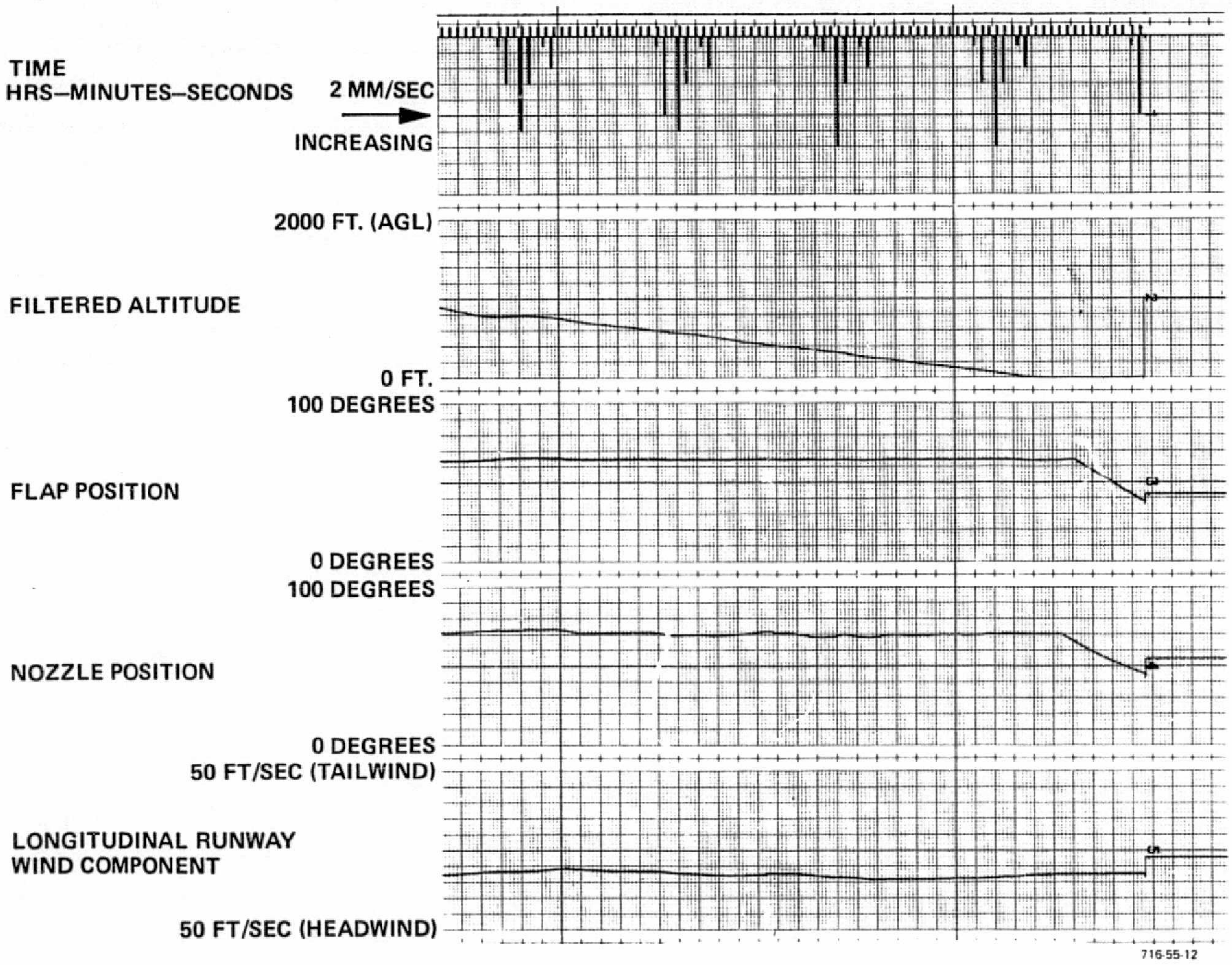


Figure 4-13
Glideslope Track and Flare, Augmentor Wing Flight Data,
Longitudinal/Vertical Data

The automatic flare was initiated at a radio altitude of approximately 47 feet as shown in Figure 4-10 at 02:46:20 when the STOLAND elevator command called for a nose-up maneuver. Touchdown occurs approximately 6 seconds later at a descent rate of 3.3 feet per second. During the flare, the airplane's attitude rotates from -2 degrees to +5 degrees and the airspeed bleeds off to 61 knots at touchdown. The flare control law uses a very high gain in the elevator loop to increase bandwidth as much as possible. Evidence of this is shown on the elevator command trace which is lightly damped with a period of about 2 seconds.

The flight data shown in Figure 4-12 and 4-13 represents inflight performance of the system during glideslope track and flare. The transition to glideslope track may be determined by the discontinuity in the glideslope error signal around 20:36:24. At this point the glideslope error is 76 feet. This error quickly reduced to less than 20 feet and remains below 20 feet for the entire approach. At the flare initiate point, 20:37:26, the glideslope error is zero and the airspeed is 69 knots. The flare initiate point is well defined by the discontinuity in the glideslope error signal (this is a scaling change). The flare lasts about 6 seconds and the touchdown sink rate is -2 feet per second. The touchdown pitch attitude and velocity are +1.5 degrees and 63 knots, respectively.

Flight glideslope track and flare performance will be discussed in more detail in Section V, Observations and Recommendations.

2. Typical Twin Otter Approach and Landing

a. Localizer Performance

Data for a simulator run illustrating the Twin Otter localizer capture performance is shown in Figures 4-14 and 4-15. It should be noted that the time scale for Figure 4-15 is in error by a factor of 1/2. Time marks in Figure 4-15 should be doubled to get the correct time.

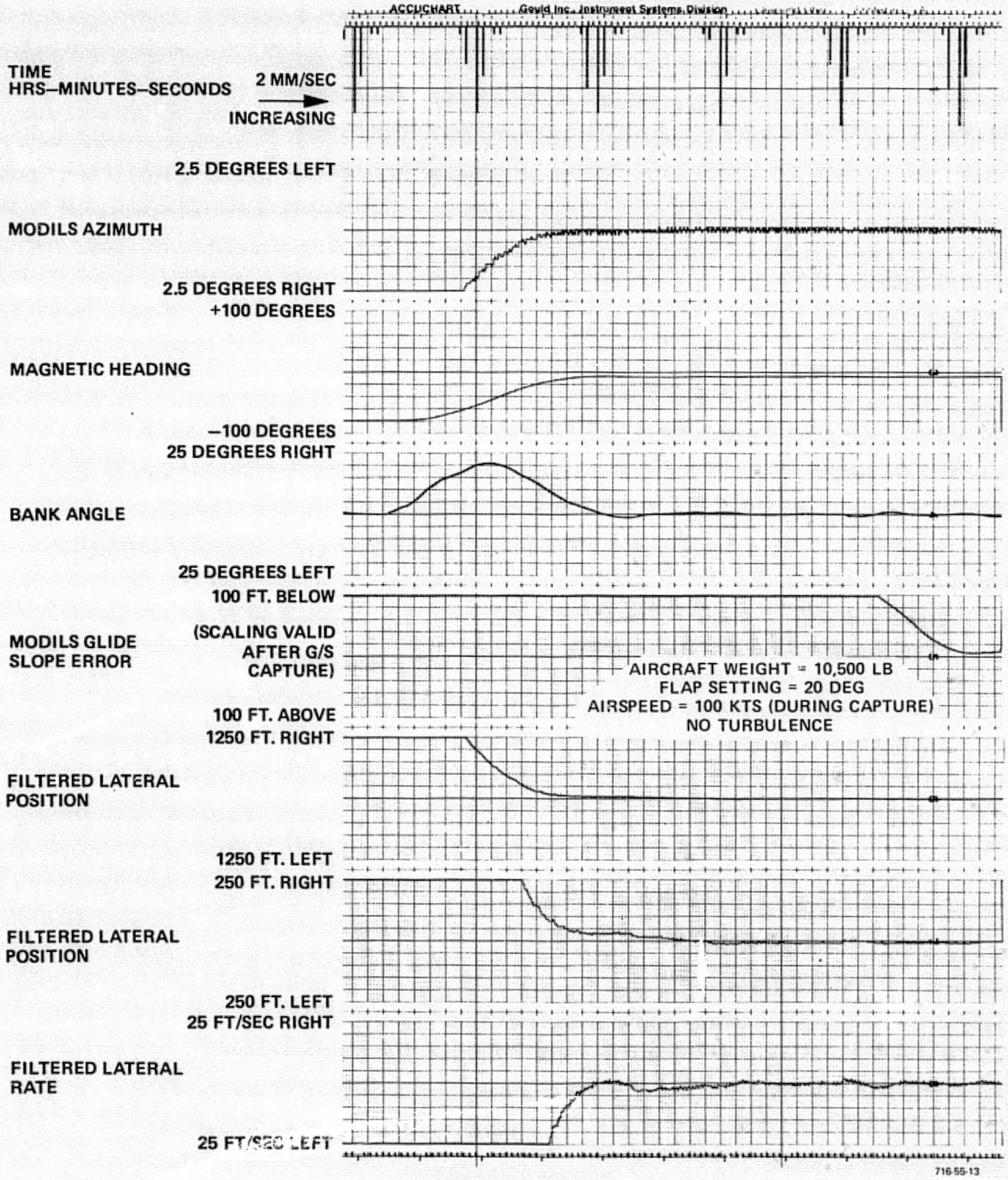


Figure 4-14
Twin Otter Simulator Data,
Localizer Capture/Track

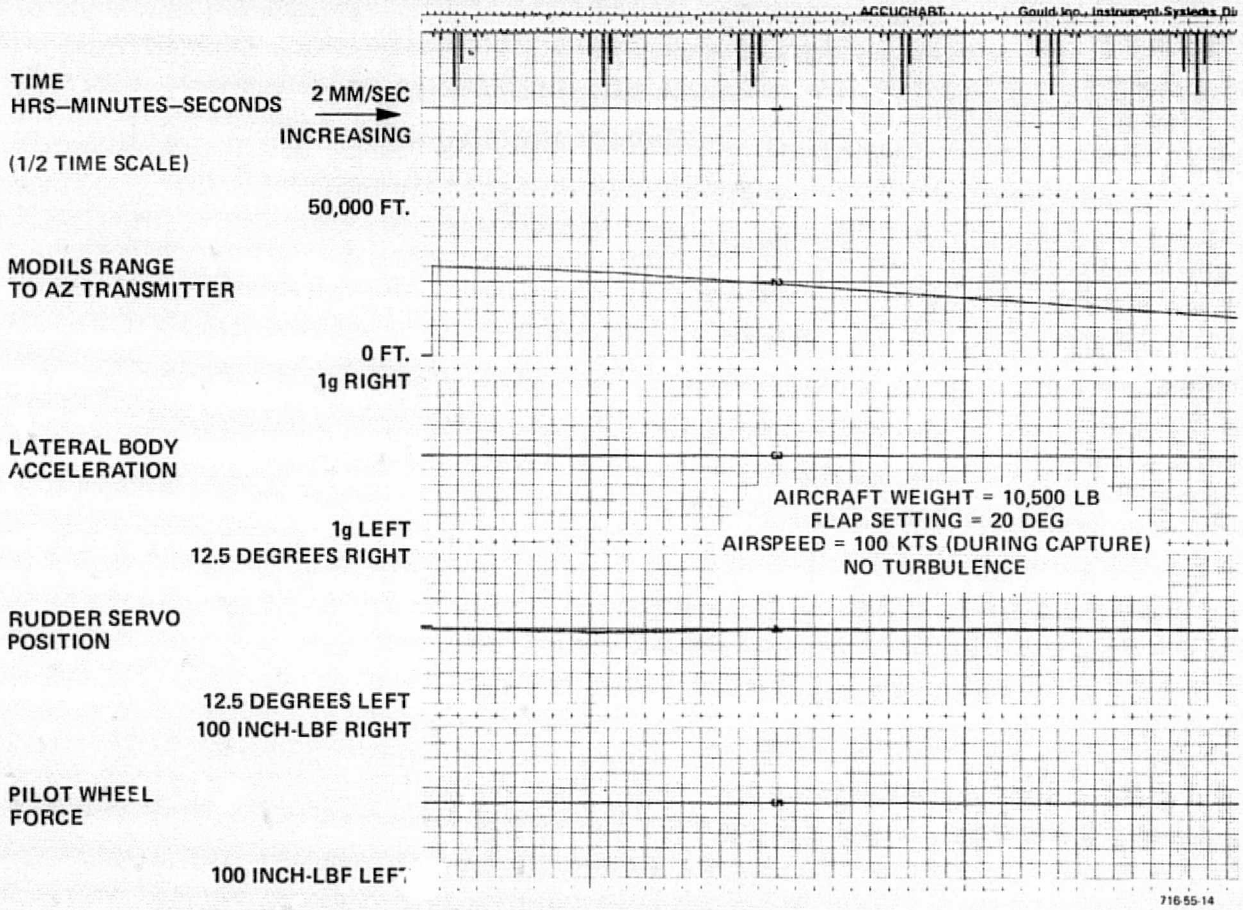


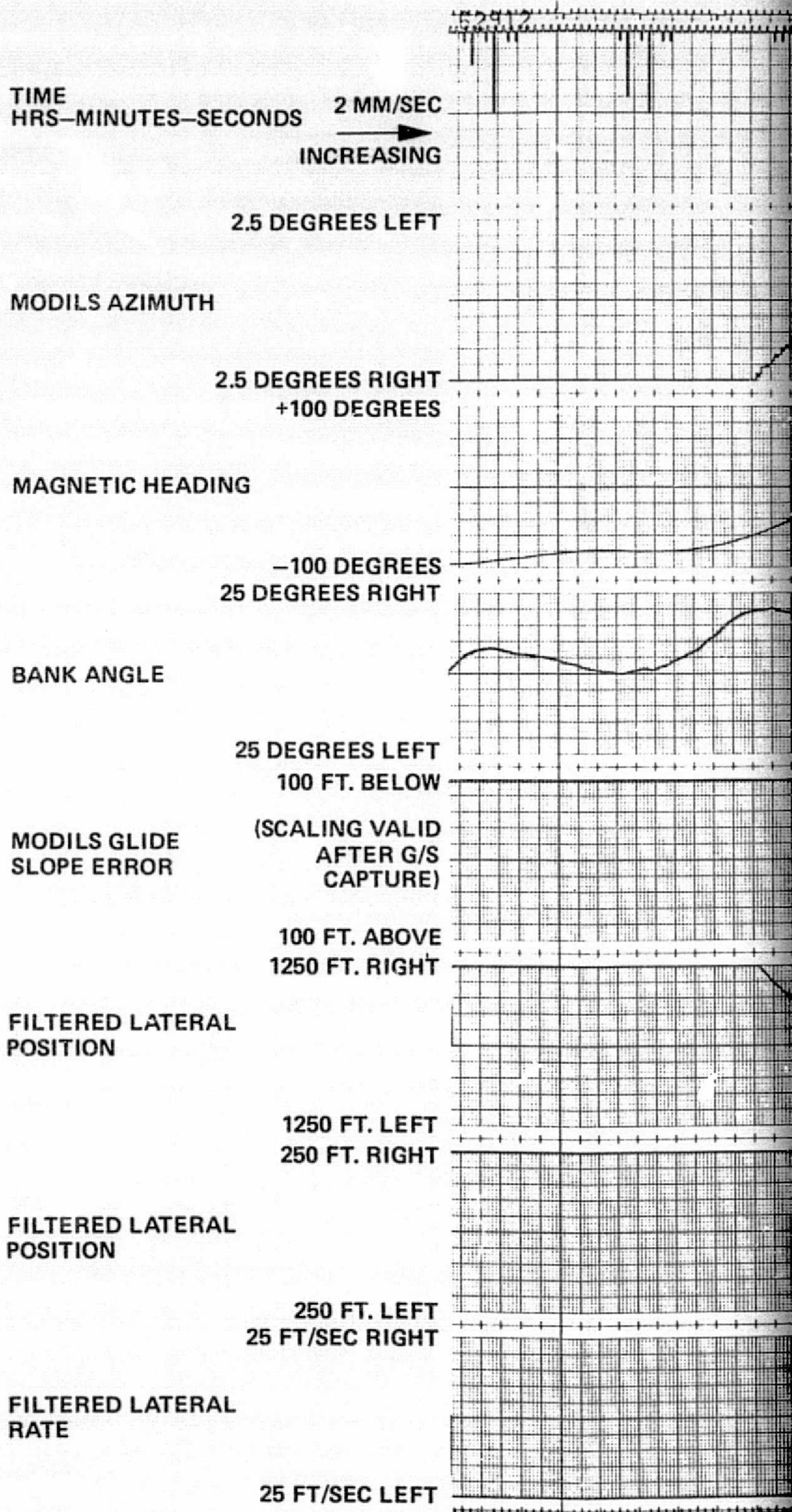
Figure 4-15
Twin Otter Simulator Data,
Localizer Capture/Track

It can be seen from Figure 4-14 that the capture maneuver started at 00:47:18 from an intercept angle of about 73 degrees (runway heading is -7.3 degrees). The maximum bank angle was 21 degrees. There was no overshoot in Y and the capture maneuver took about 40 seconds. Figure 4-15 shows that the capture ocurred at about 5 miles with no wheel force applied by the pilot.

Figure 4-16 and 4-17 demonstrate the same capture in light turbulence with an rms value of 2.5 feet per second. It can be seen that the turbulence does not significantly affect the capture maneuver. Bank angle excursions from zero to about 2 degrees were required to maintain zero lateral error with this level of turbulence.

The simulated MODILS azimuth signal shown in Figure 4-14 and 4-16 has a "dither" model signal superimposed upon it, which simulates the actual dither which is observed on the real MODILS azimuth signal. Traces of this dither characteristic appear in the Y and $\dot{Y}$ signals since these quantitites are derived from the MODILS azimuth signal. It should be noted that the azimuth signal in these figures is recorded like all the other signals at five samples per second and, therefore, it does not reflect the true high frequency content of the signal.

A sample of in-flight localizer capture/track performance is shown in Figures 4-18 and 4-19. The localizer capture occurs at 18:29:23 from a 19-degree left bank at an intercept angle of about 70 degrees. This flight record demonstrates the frequently used STOLAND pilot's method of capturing the localizer from a non-zero bank condition which has been established with control wheel steering. This method of capture was used by the pilot to minimize time between successive approaches and does not necessarily represent an initial setup for capture that would be used in a typical STOL approach to the runway. Under these conditions, the localizer capture bank command starts at zero and rapidly increases while the aircraft bank angle decreases toward the command until the command becomes greater than the bank angle. This explains the initial dip in the bank angle early in the capture and may partially explain the 125-foot overshoot observed in Y.


52912
TIME
HRS–MINUTES–SECONDS
2 MM/SEC
INCREASING
2.5 DEGREES LEFT
MODILS AZIMUTH
2.5 DEGREES RIGHT
+100 DEGREES
MAGNETIC HEADING
–100 DEGREES
25 DEGREES RIGHT
BANK ANGLE
25 DEGREES LEFT
100 FT. BELOW
MODILS GLIDE SLOPE ERROR
(SCALING VALID AFTER G/S CAPTURE)
100 FT. ABOVE
1250 FT. RIGHT
FILTERED LATERAL POSITION
1250 FT. LEFT
250 FT. RIGHT
FILTERED LATERAL POSITION
250 FT. LEFT
25 FT/SEC RIGHT
FILTERED LATERAL RATE
25 FT/SEC LEFT

FOLDOUT FRA

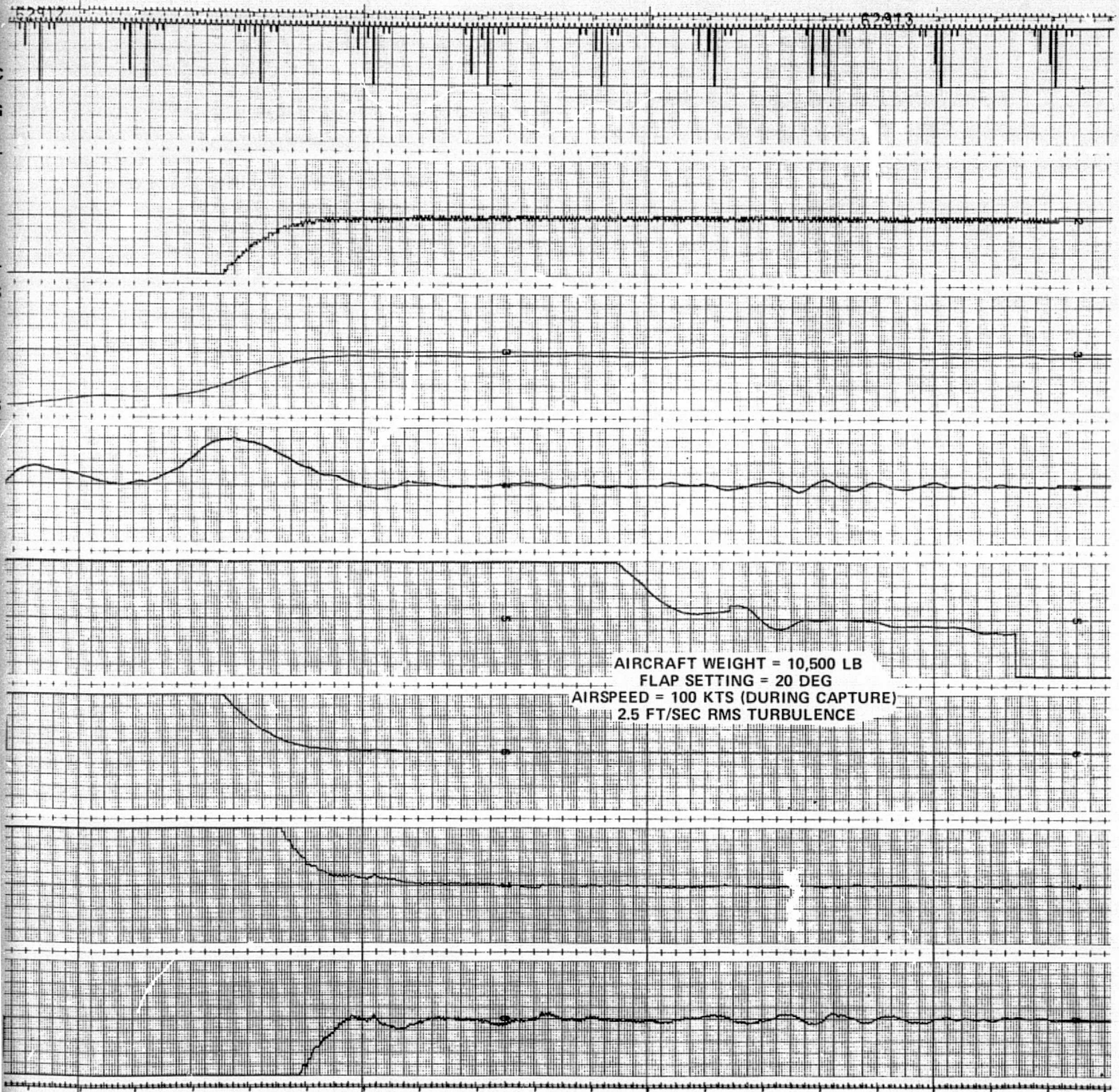
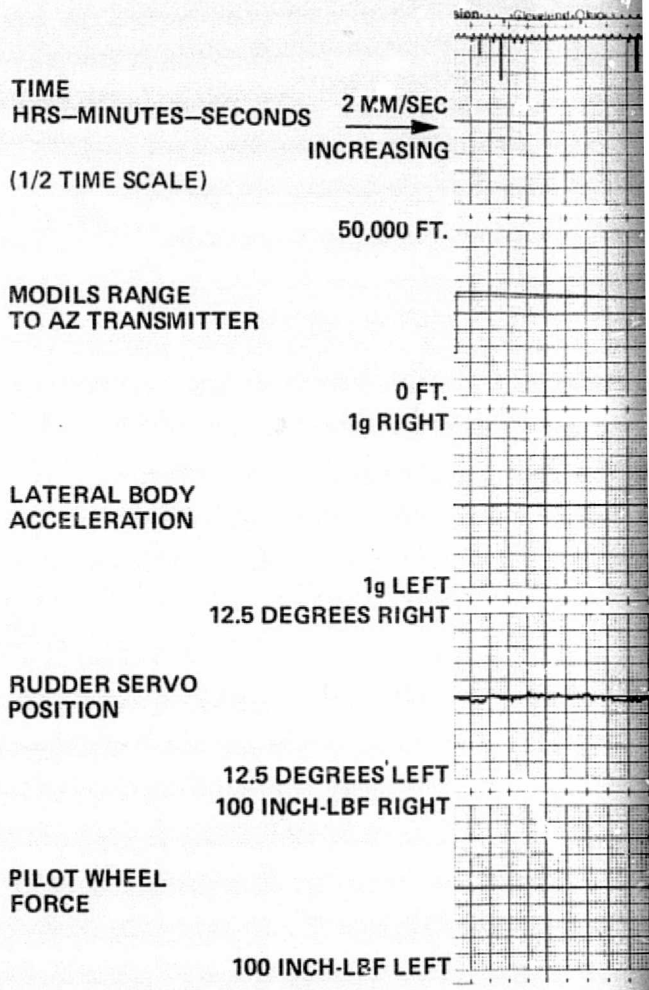


Figure 4-16
Twin Otter Simulator Data,
Localizer Capture/Track

FOLDOUT FRAME 2


TIME
HRS–MINUTES–SECONDS
2 MM/SEC
INCREASING
(1/2 TIME SCALE)
50,000 FT.
MODILS RANGE
TO AZ TRANSMITTER
0 FT.
1g RIGHT
LATERAL BODY
ACCELERATION
1g LEFT
12.5 DEGREES RIGHT
RUDDER SERVO
POSITION
12.5 DEGREES LEFT
100 INCH-LBF RIGHT
PILOT WHEEL
FORCE
100 INCH-LBF LEFT

FOLDOUT

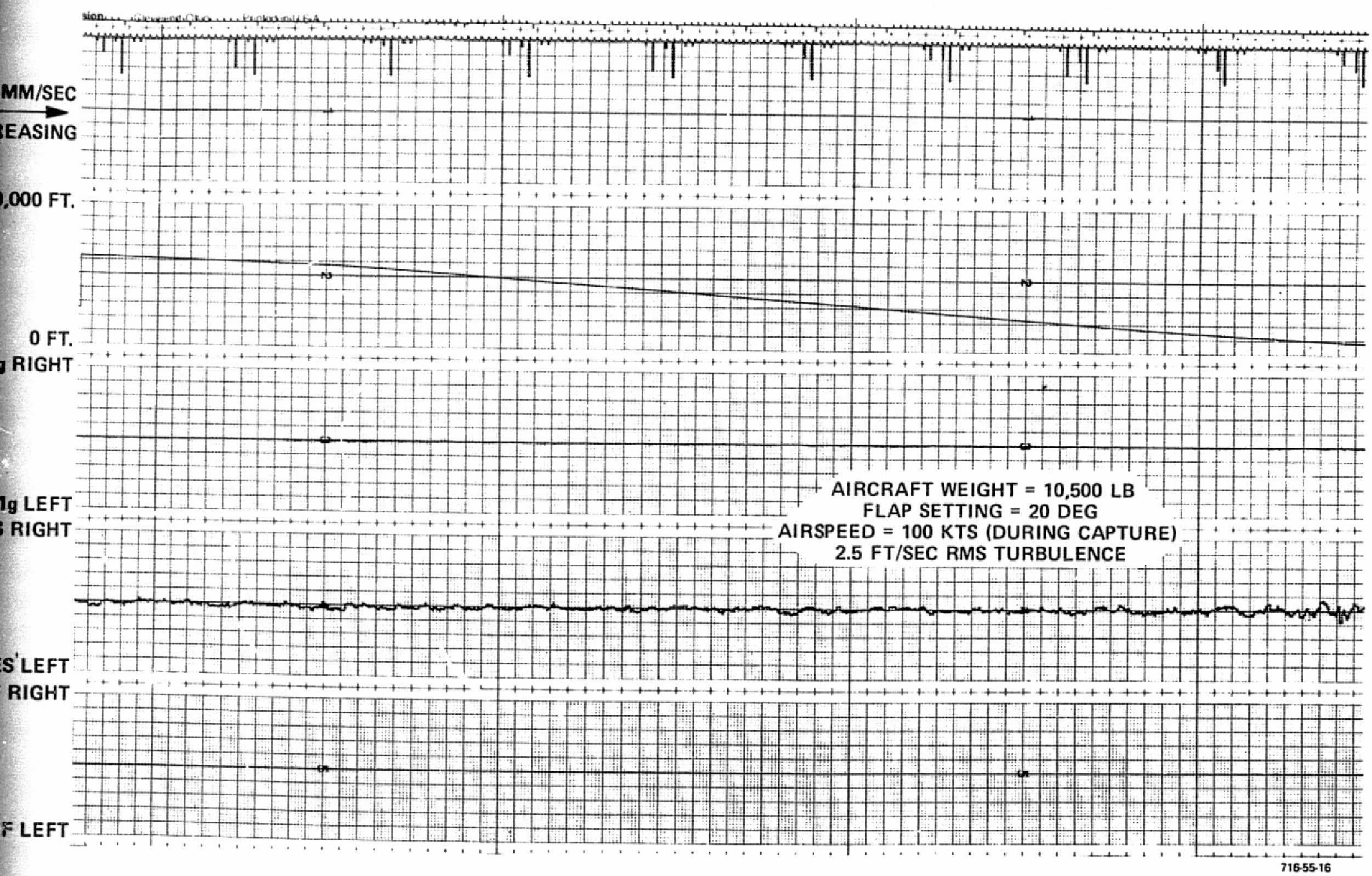
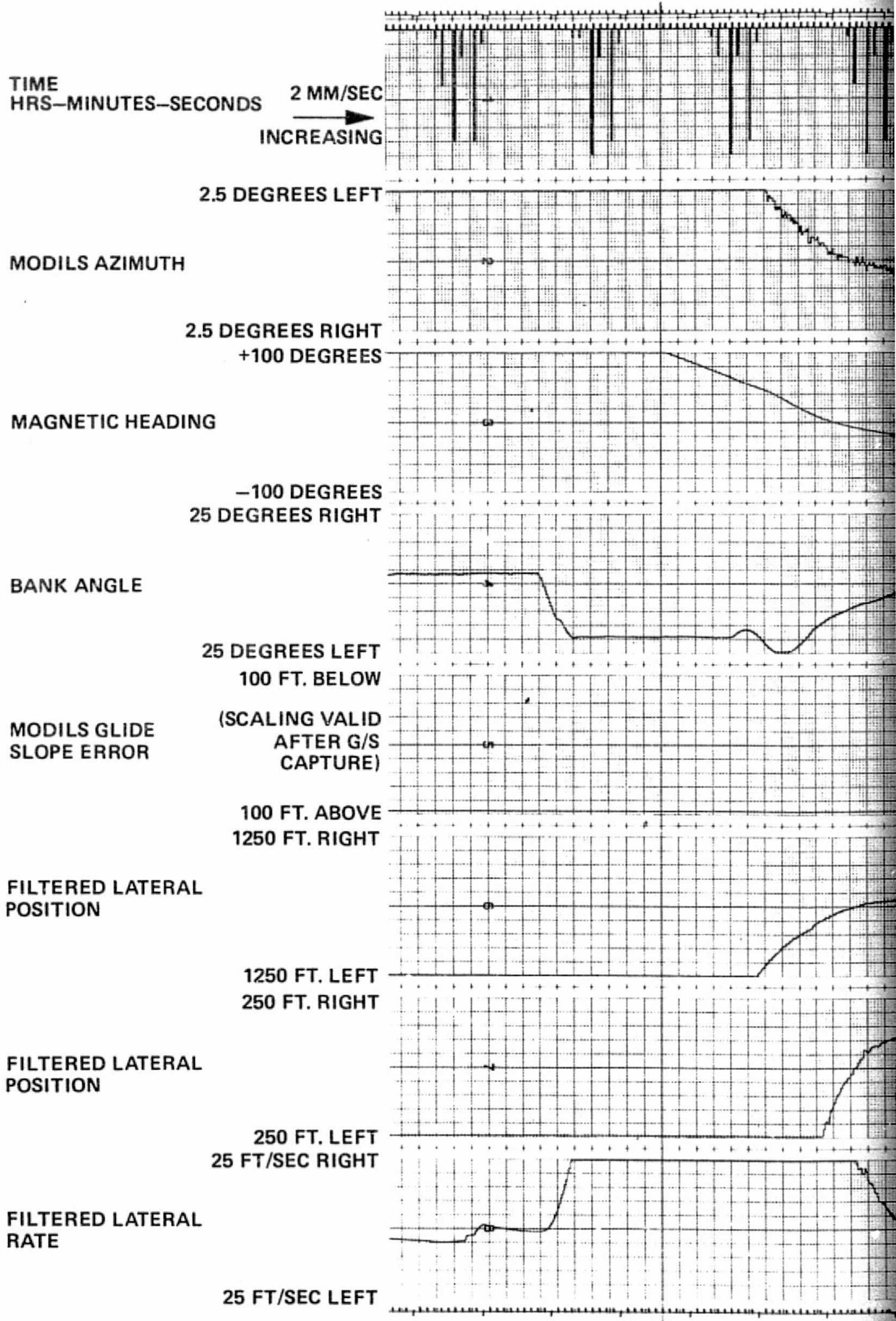
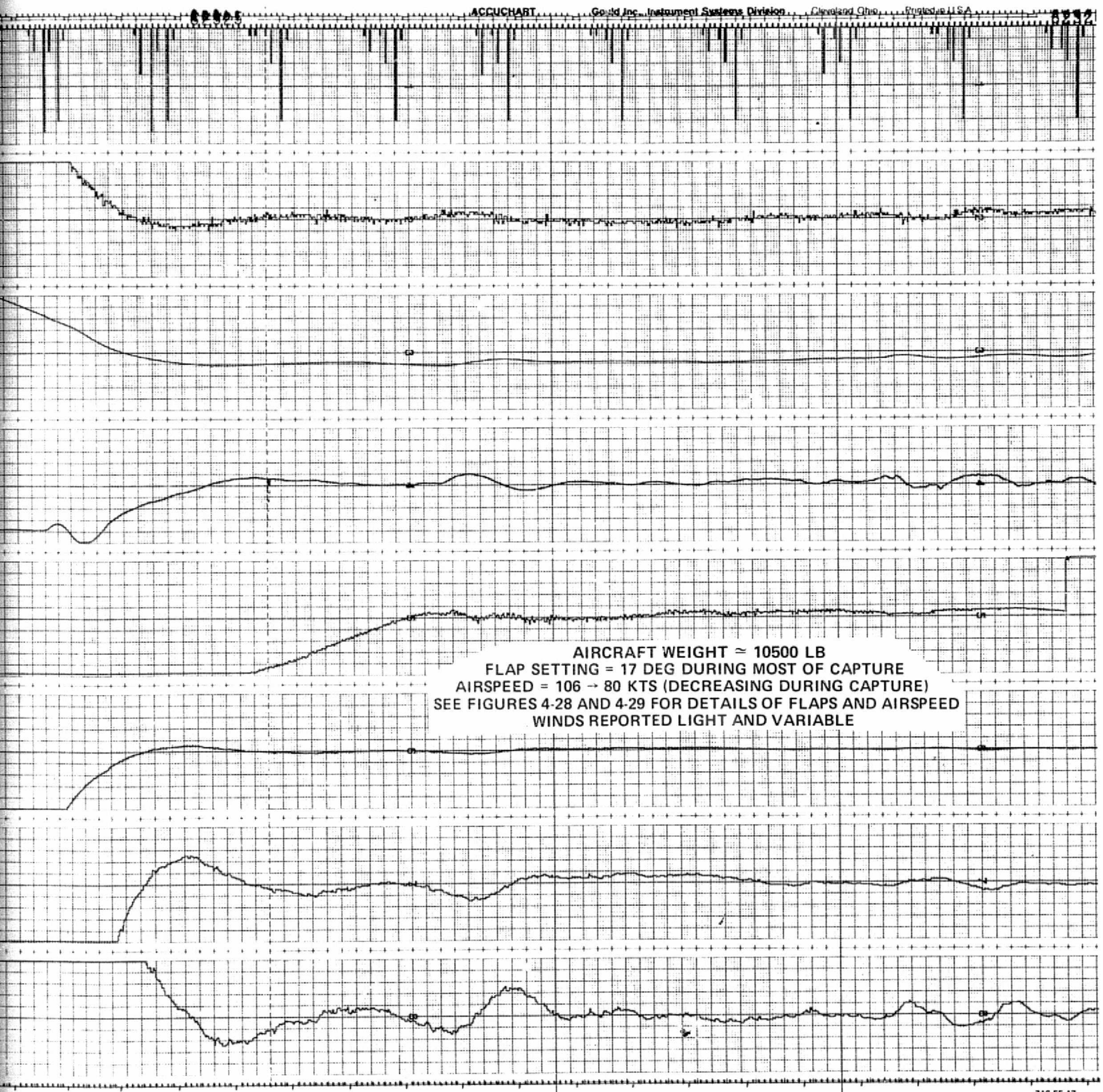


Figure 4-17
Twin Otter Simulator Data,
Localizer Capture/Track

FOLDOUT FR... 2



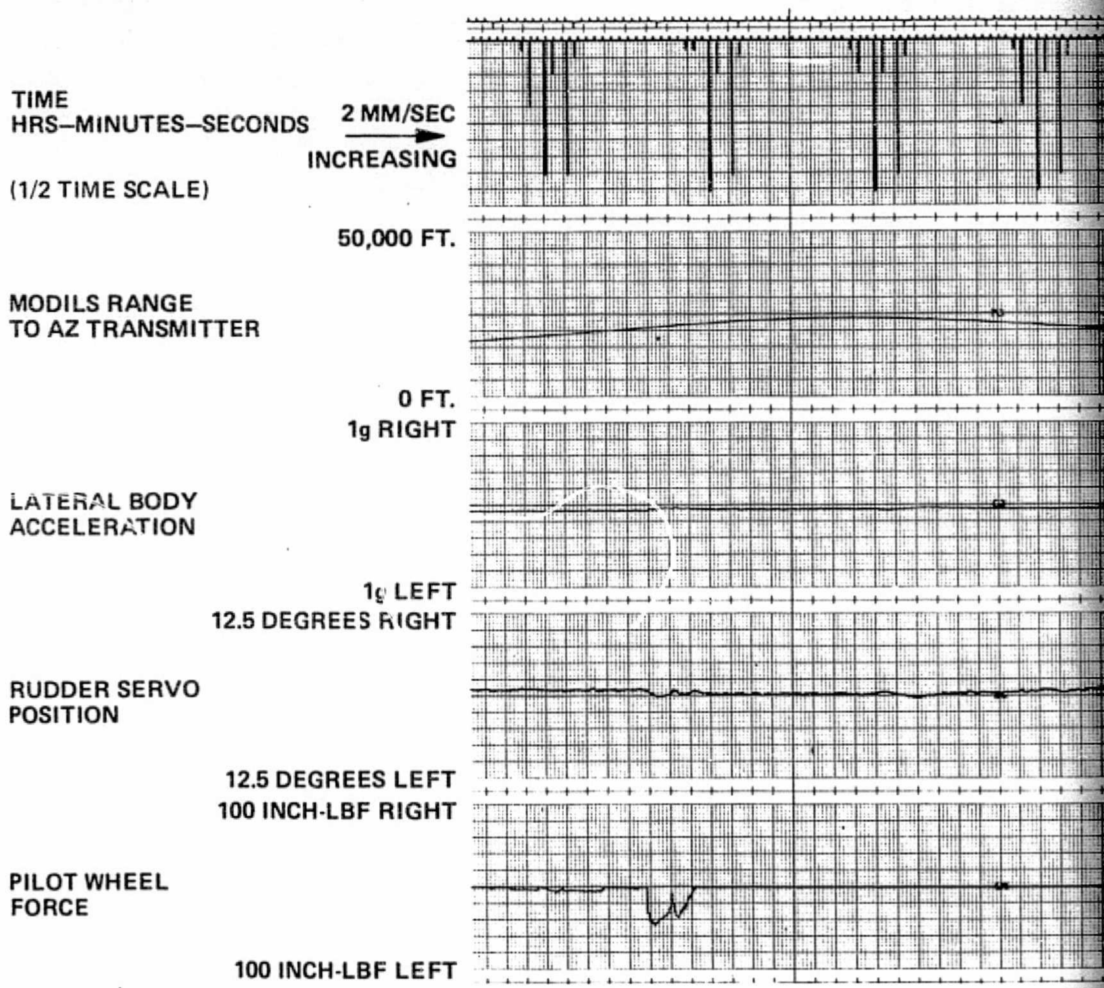
TIME
HRS–MINUTES–SECONDS
2 MM/SEC
INCREASING
2.5 DEGREES LEFT
MODILS AZIMUTH
2.5 DEGREES RIGHT
+100 DEGREES
MAGNETIC HEADING
–100 DEGREES
25 DEGREES RIGHT
BANK ANGLE
25 DEGREES LEFT
100 FT. BELOW
MODILS GLIDE SLOPE ERROR
(SCALING VALID AFTER G/S CAPTURE)
100 FT. ABOVE
1250 FT. RIGHT
FILTERED LATERAL POSITION
1250 FT. LEFT
250 FT. RIGHT
FILTERED LATERAL POSITION
250 FT. LEFT
25 FT/SEC RIGHT
FILTERED LATERAL RATE
25 FT/SEC LEFT



FOLDOUT F.

2

Figure 4-18
Twin Otter Flight Data,
Localizer Capture/Track


TIME
HRS–MINUTES–SECONDS
2 MM/SEC
INCREASING
(1/2 TIME SCALE)
50,000 FT.
MODILS RANGE
TO AZ TRANSMITTER
0 FT.
1g RIGHT
LATERAL BODY
ACCELERATION
1g LEFT
12.5 DEGREES RIGHT
RUDDER SERVO
POSITION
12.5 DEGREES LEFT
100 INCH-LBF RIGHT
PILOT WHEEL
FORCE
100 INCH-LBF LEFT

FOLDOUT

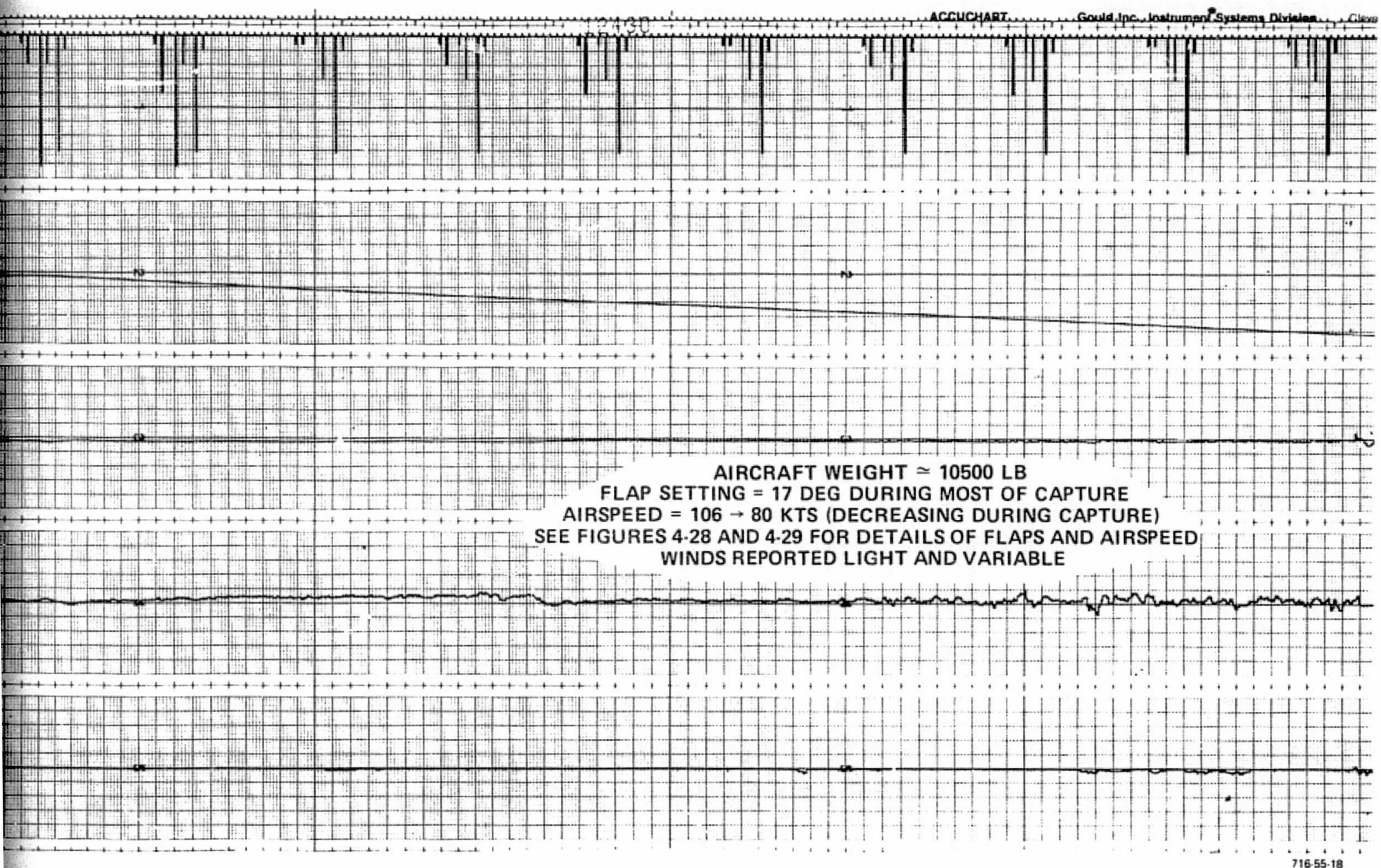


Figure 4-19
Twin Otter Flight Data,
Localizer Capture/Track

FOLDOUT

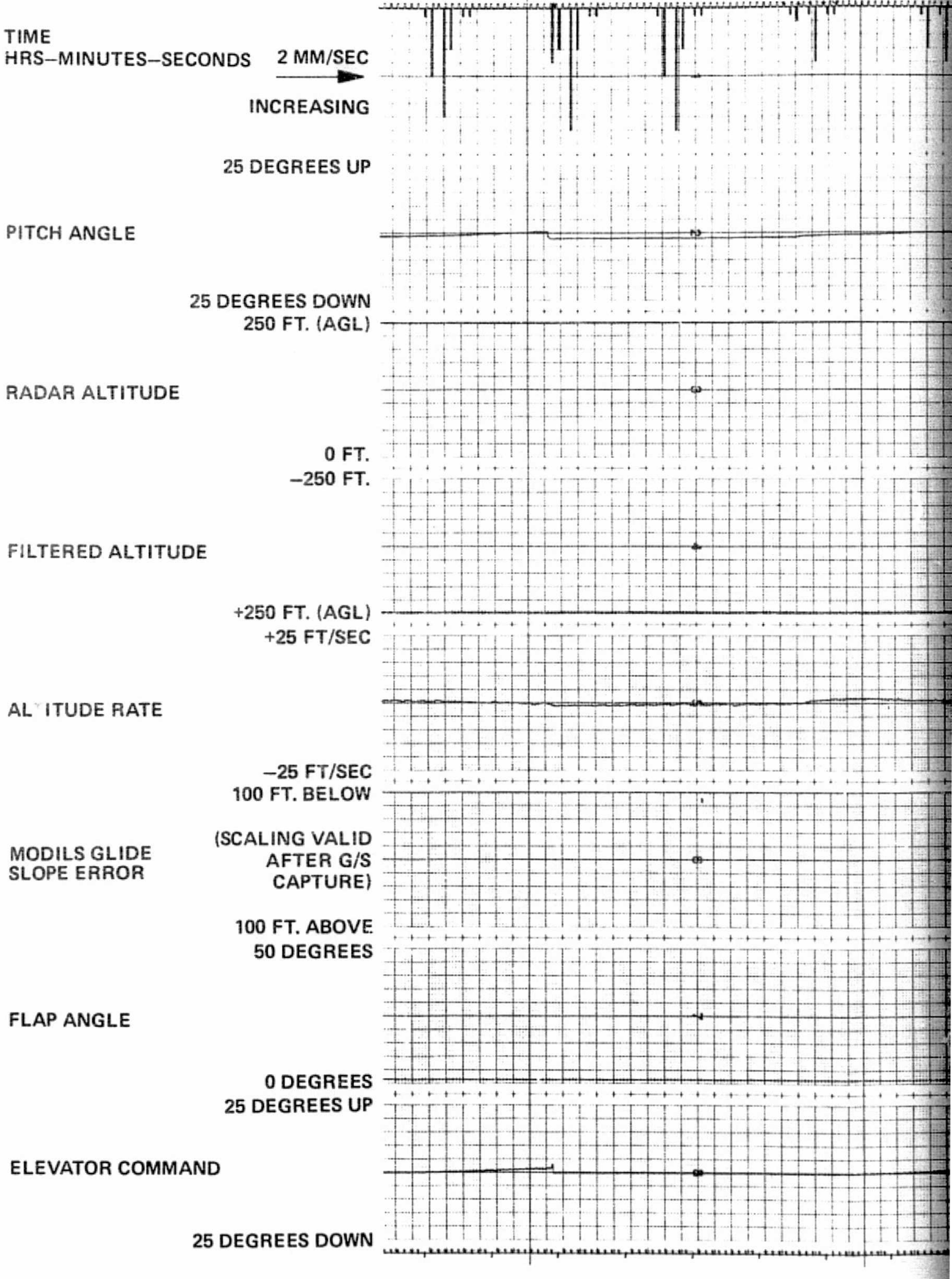
2

The flight performance demonstrated in Figure 4-18 is not as good as the simulator performance shown in Figure 4-16. This degraded flight performance can be explained by factors which were observed to be present in flight but were not simulated in the simulation run shown. The first factor is navigation errors due to gyro errors in roll attitude which are known to occur in decelerating, turning approaches. These errors degrade the navigation estimates and result in degraded capture performance. The errors are gradually washed out as the localizer track progresses. The second factor which has been recorded in flight is a yawing moment effect due to assymetrical thrust changes when the throttles are moved to hold speed. (Refer to torque pressure recordings in Figure 4-29 which give vertical/longitudinal data for the same approach as shown in Figure 4-18.) The engine yawing moment effect degrades the tightness of the tracking by driving the aircraft off the lateral path. Both factors mentioned here are discussed in Section V, Observations and Recommendations.

b. Automatic Speed Reduction and Configuration Change

A simulator run which demonstrates the system performance during a fully automatic speed reduction and configuration change followed by an approach to flare and touchdown is shown in Figures 4-20 and 4-21. The time marks in Figure 4-21 should be doubled to obtain the correct time.

The run started (about 00:39:34) with the aircraft in a clean configuration flying at 135 knots (228 feet per second). The FULL AUTO button was activated at about 00:40:10 (at 5 miles from the touchdown point) where the torque pressures were reduced as the throttles were commanded to initiate the speed reduction. From this point on no further pilot inputs were required. The speed was commanded down to 68 knots from 135 knots in a smooth fashion at approximately 1 knot per second. The flaps were automatically deployed to 20 degrees as the airspeed went below 100 knots and to 40 degrees as the airspeed went below 85 knots. The system held altitude until 00:41:45 when the descending 6-degree MODILS glideslope was captured. The 68-knot, 6-degree approach resulted in a 12 foot per second rate of descent. The pitch attitude during the descent was -10 degrees. A glideslope error of essentially zero feet was maintained up to the flare initiate point. The


TIME
HRS–MINUTES–SECONDS
2 MM/SEC
INCREASING
25 DEGREES UP
PITCH ANGLE
25 DEGREES DOWN
250 FT. (AGL)
RADAR ALTITUDE
0 FT.
–250 FT.
FILTERED ALTITUDE
+250 FT. (AGL)
+25 FT/SEC
ALTITUDE RATE
–25 FT/SEC
100 FT. BELOW
MODILS GLIDE SLOPE ERROR
(SCALING VALID AFTER G/S CAPTURE)
100 FT. ABOVE
50 DEGREES
FLAP ANGLE
0 DEGREES
25 DEGREES UP
ELEVATOR COMMAND
25 DEGREES DOWN

FOLDOUT

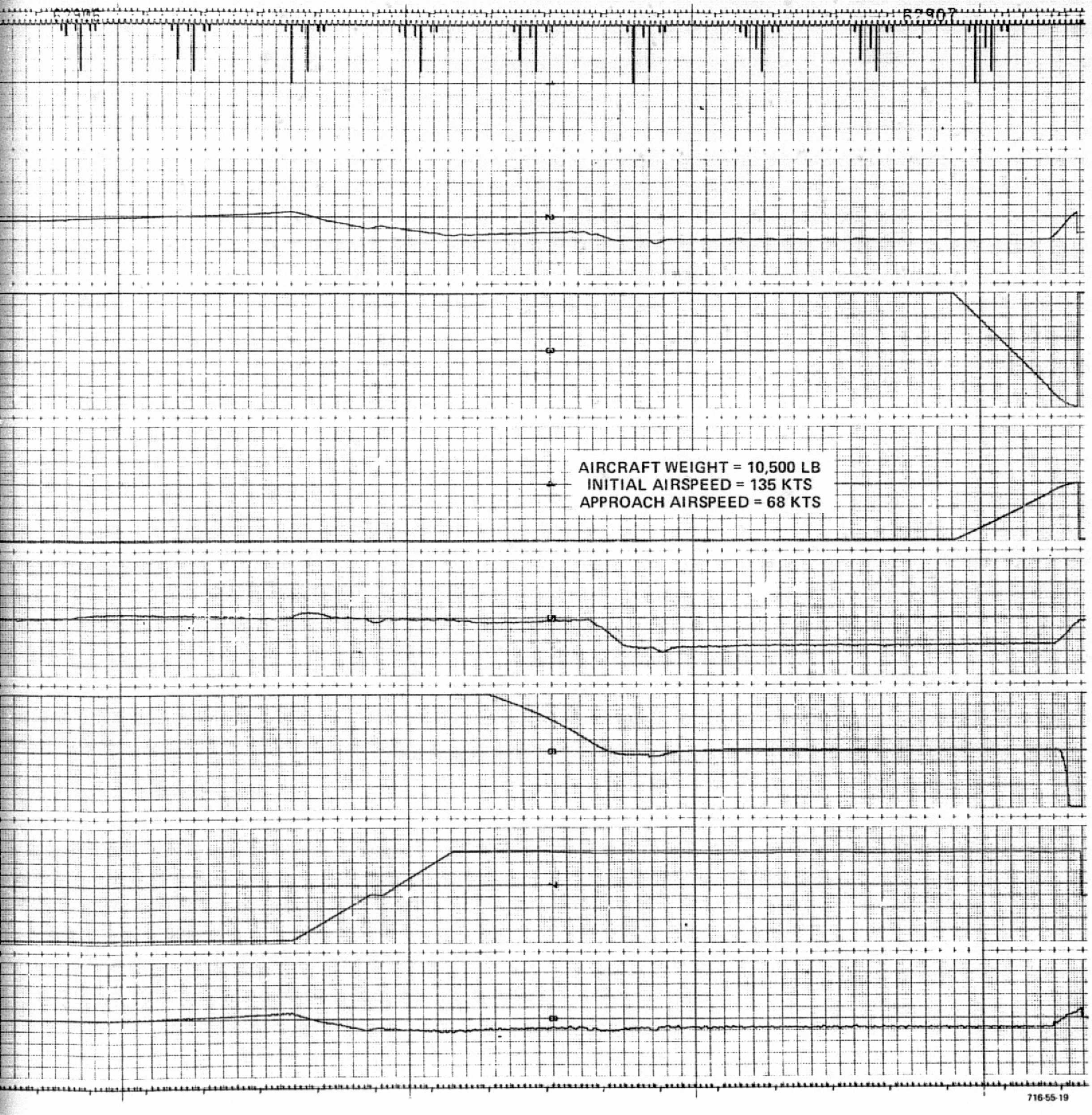


Figure 4-20
Twin Otter Simulator Data,
Automatic Speed Reduction
and Configuration Change

FOLDOUT

2

TIME
HRS–MINUTES–SECONDS

(1/2 TIME SCALE)

2 MM/SEC

INCREASING

50 LBF NOSE UP

PILOT COLUMN
FORCE

50 LBF NOSE DOWN

250 FT/SEC

CALIBRATED AIRSPEED

0 FT/SEC

+45 PSI

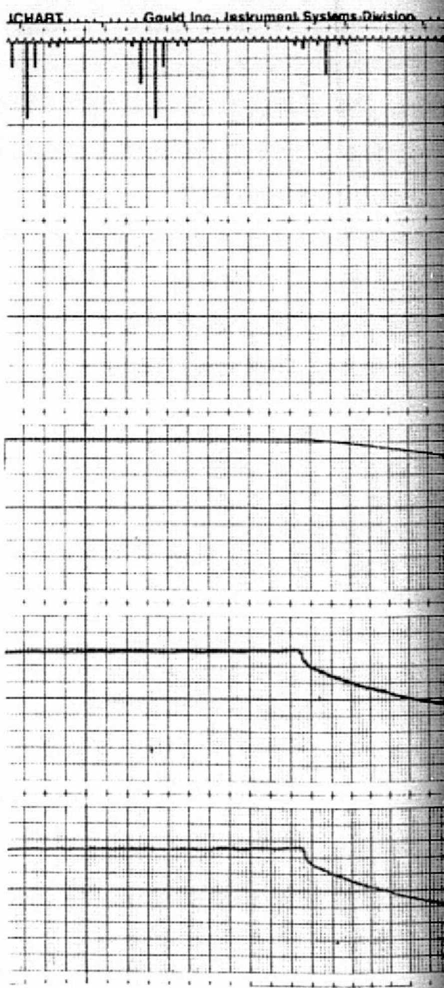
RIGHT TORQUE
PRESSURE

–5 PSI

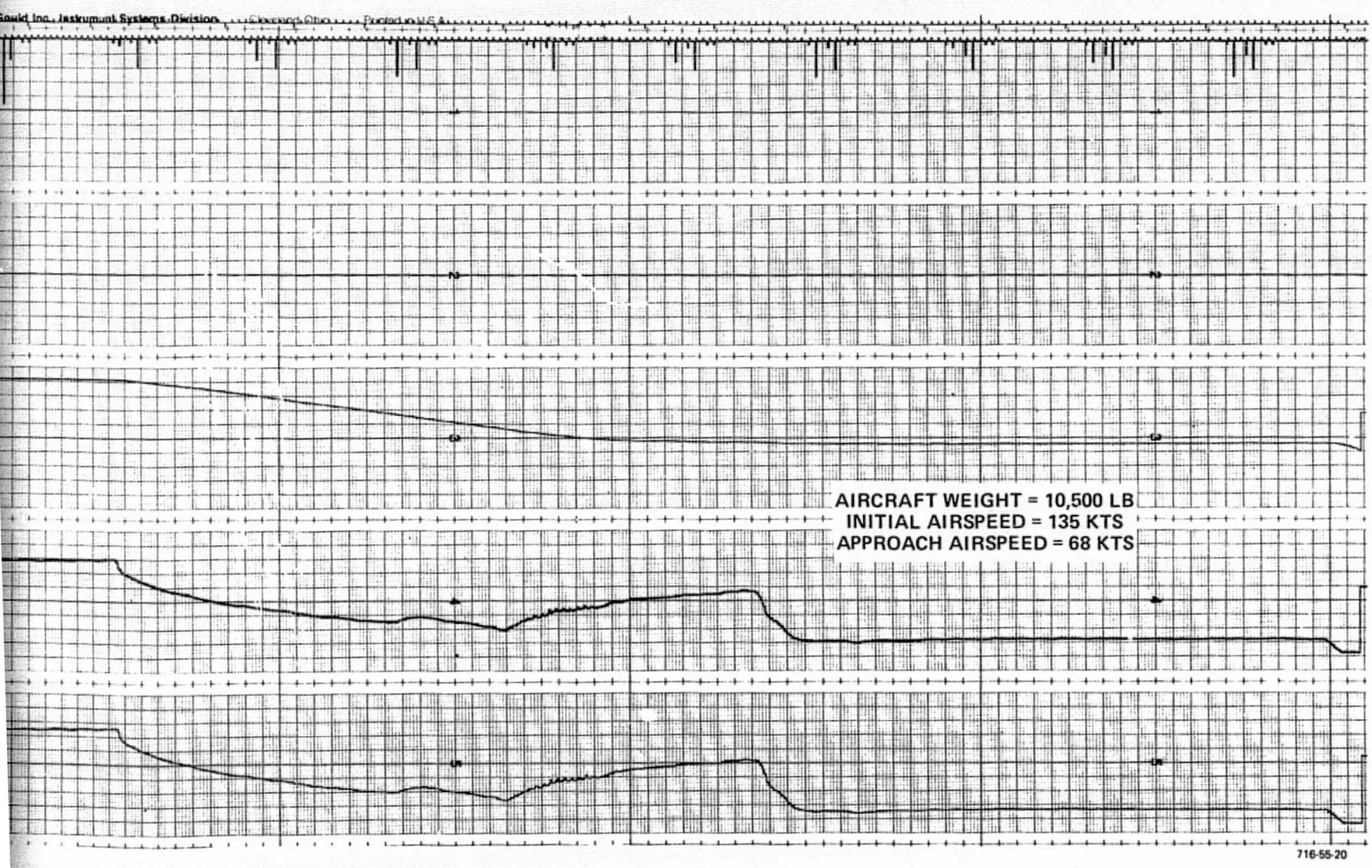
+45 PSI

LEFT TORQUE
PRESSURE

–5 PSI



FOLDOUT FRAME



FOLDOUT FRAME 2

Figure 4-21
Twin Otter Simulator Data,
Automatic Speed Reduction
and Configuration Change

flare maneuver was automatically initiated at 00:43:04 at an altitude of about 39 feet. The flare lasted about 5 seconds and the touchdown occurred with a sink rate of 2 feet per second and a pitch attitude of +1.5 degrees.

c. Glideslope Capture/Track and Flare

Simulator system performance is presented in Figures 4-22 through 4-27. In each case vertical/longitudinal variables have been recorded to demonstrate the glideslope capture and track performance on a 6-degree glideslope to a flareout and touchdown.

Figures 4-22 and 4-23 represent the nominal case with the glideslope capture occurring around 00:14:35 and flare at 00:15:58. The flare lasted 6.5 seconds and resulted in a touchdown sink rate of 3 feet per second with a pitch attitude of +3 degrees (the design value).

Figures 4-24 and 4-25 represent a 10-knot headwind case. The flare lasted 6 seconds with a resulting touchdown sink rate of 2.5 feet per second and a touchdown pitch attitude of +3 degrees.

Figures 4-26 and 4-27 represent an approach in a 10-knot headwind with 2.5 rms turbulence. The glideslope capture occurs around 00:32:40 and the flare maneuver at 00:34:15 at about 40 feet. The flare lasts for 6.5 seconds and results in a touchdown sink rate of 3.8 feet per second and a touchdown attitude of +4 degrees.

Figures 4-28 and 4-29 present flight data which was recorded under similar conditions to those existing in the simulator runs represented in Figures 4-26 and 4-27. It should be noted, however, that the aircraft flap setting in flight was 35 degrees as opposed to 40 degrees for the simulator run, since a mechanical problem with the airframe on this flight prevented the flaps from deploying any further. This difference in flap setting explains most of the difference in pitch attitude on the glideslope between the simulator and flight data. Simulator data would show that a 5-degree change in flap setting should change the pitch attitude by about 1.5 degrees, whereas the recorded difference was on the order of 2 to 3 degrees. The higher pitch attitude in flight is consistent with the smaller flap setting.

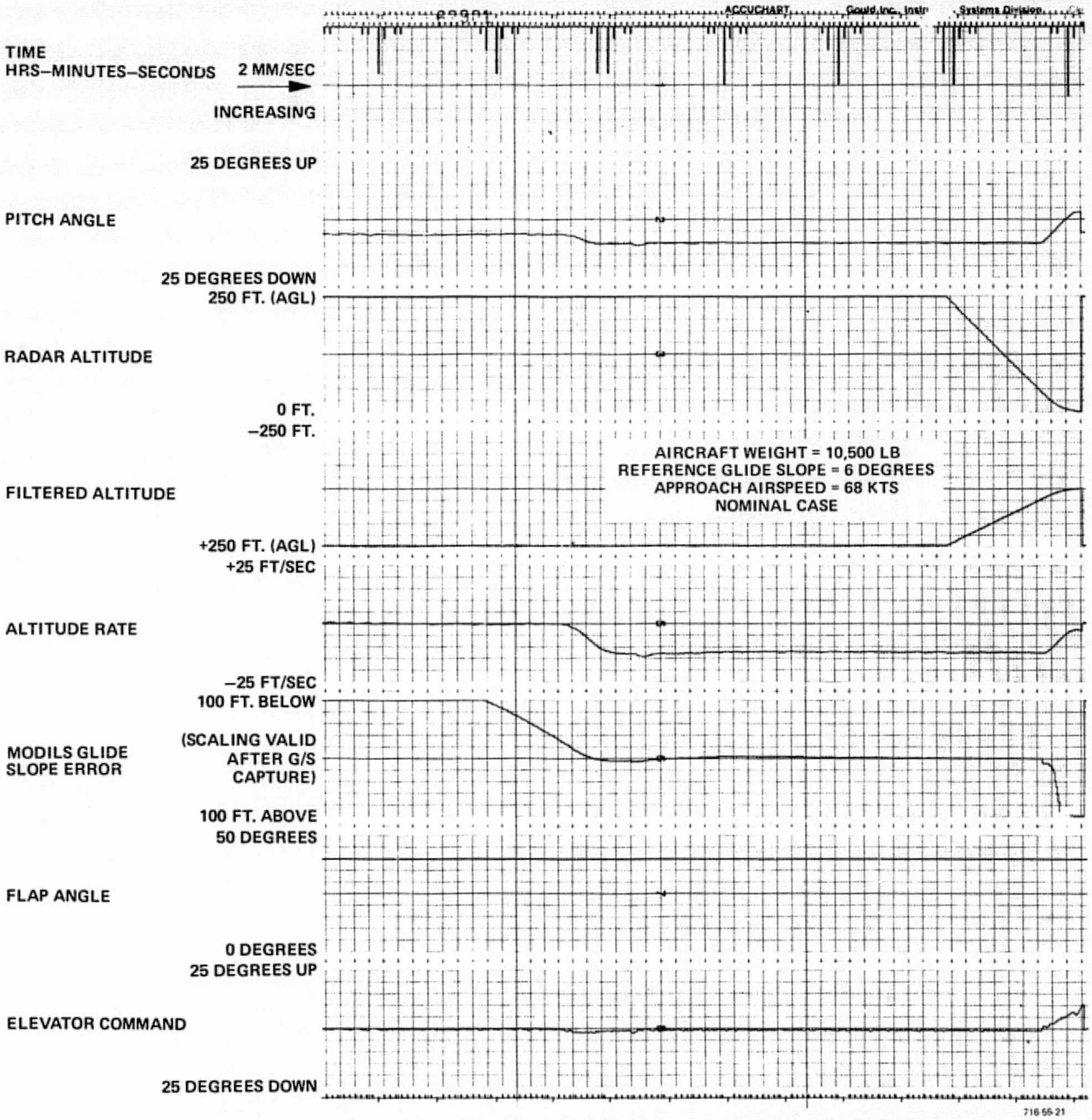


Figure 4-22
Twin Otter Simulator Data,
Glideslope Capture/Track and Flare

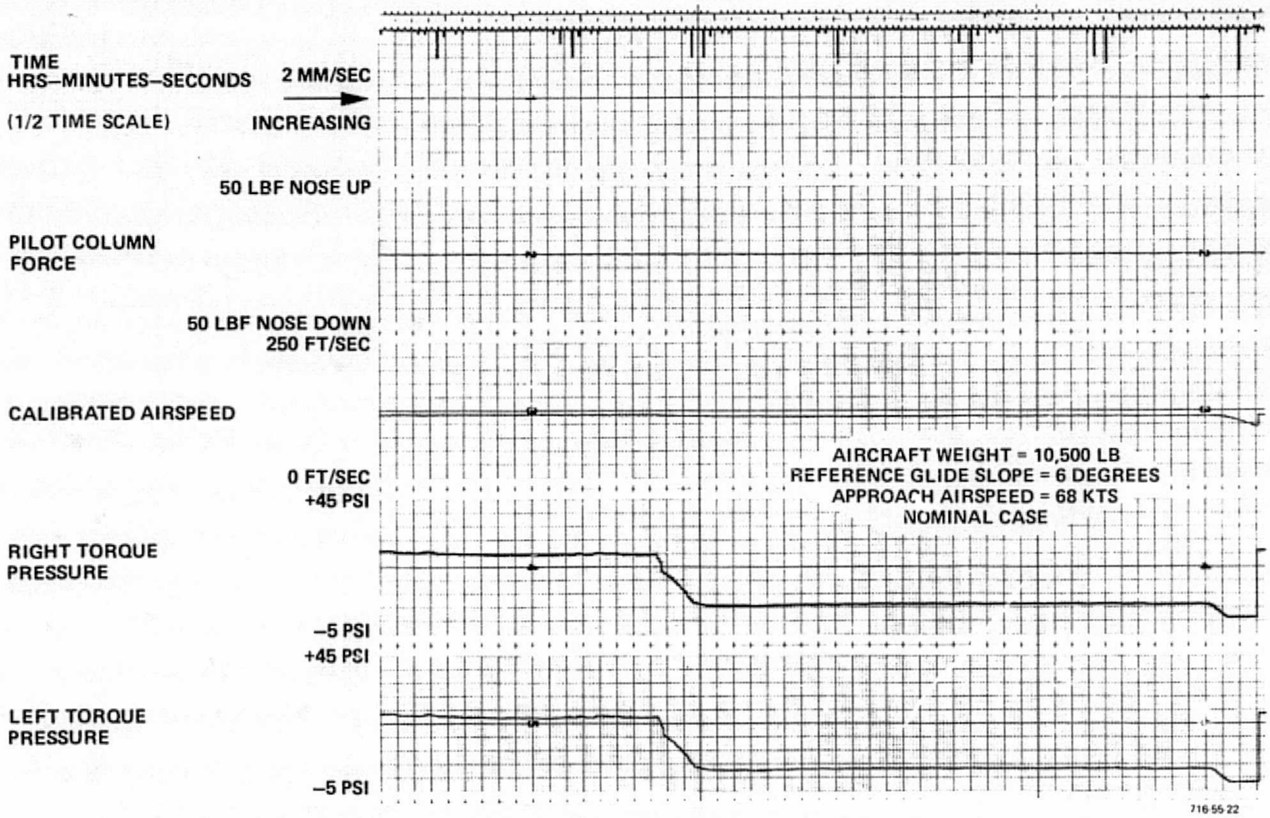


Figure 4-23
Twin Otter Simulator Data,
Glideslope Capture/Track and Flare

TIME
HRS–MINUTES–SECONDS 2 MM/SEC
INCREASING

25 DEGREES UP

PITCH ANGLE

25 DEGREES DOWN
250 FT. (AGL)

RADAR ALTITUDE

0 FT.
–250 FT.

FILTERED ALTITUDE

+250 FT. (AGL)
+25 FT/SEC

ALTITUDE RATE

–25 FT/SEC
100 FT. BELOW

MODILS GLIDE SLOPE ERROR
(SCALING VALID AFTER G/S CAPTURE)

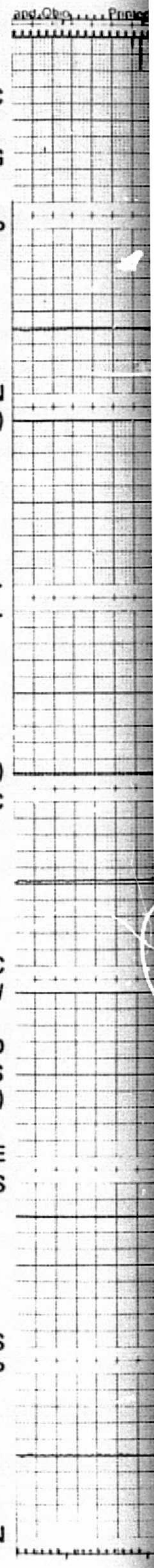
100 FT. ABOVE
50 DEGREES

FLAP ANGLE

0 DEGREES
25 DEGREES UP

ELEVATOR COMMAND

25 DEGREES DOWN



FOLDOUT FRAME

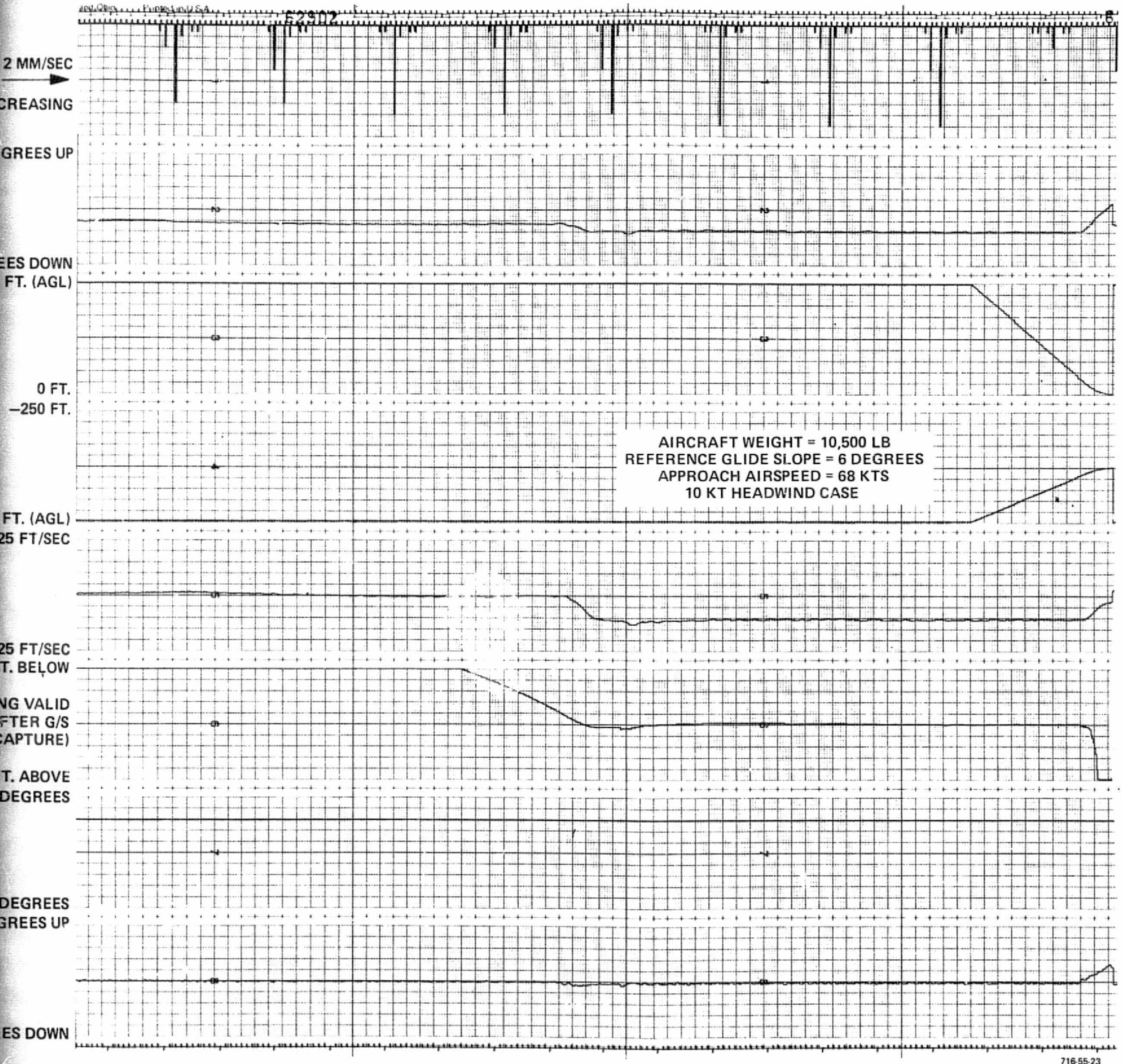


Figure 4-24
Twin Otter Simulator Data,
Glideslope Capture/Track and Flare

FOLDOUT FRAME 2

TIME
HRS–MINUTES–SECONDS

(1/2 TIME SCALE)

2 MM/SEC

INCREASING

50 LBF NOSE UP

PILOT COLUMN
FORCE

50 LBF NOSE DOWN

250 FT/SEC

CALIBRATED AIRSPEED

0 FT/SEC

+45 PSI

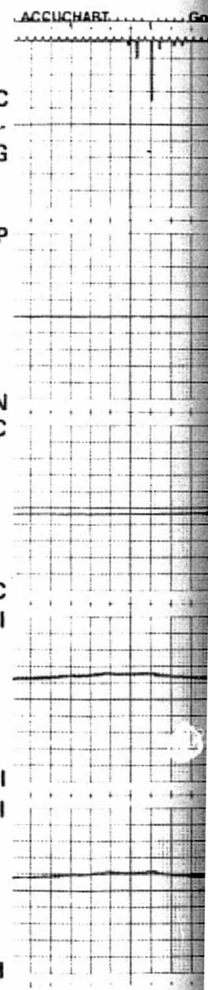
RIGHT TORQUE
PRESSURE

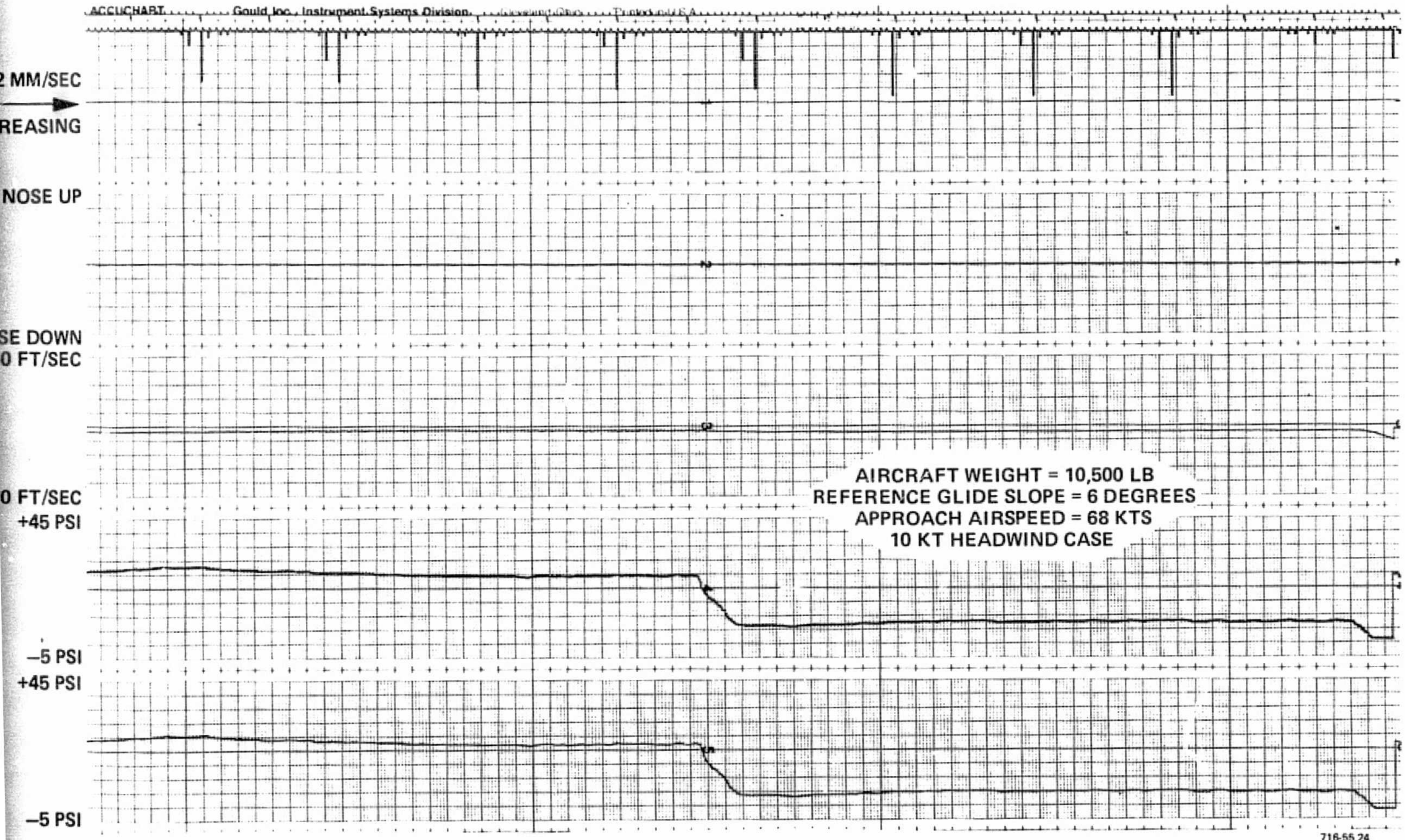
–5 PSI

+45 PSI

LEFT TORQUE
PRESSURE

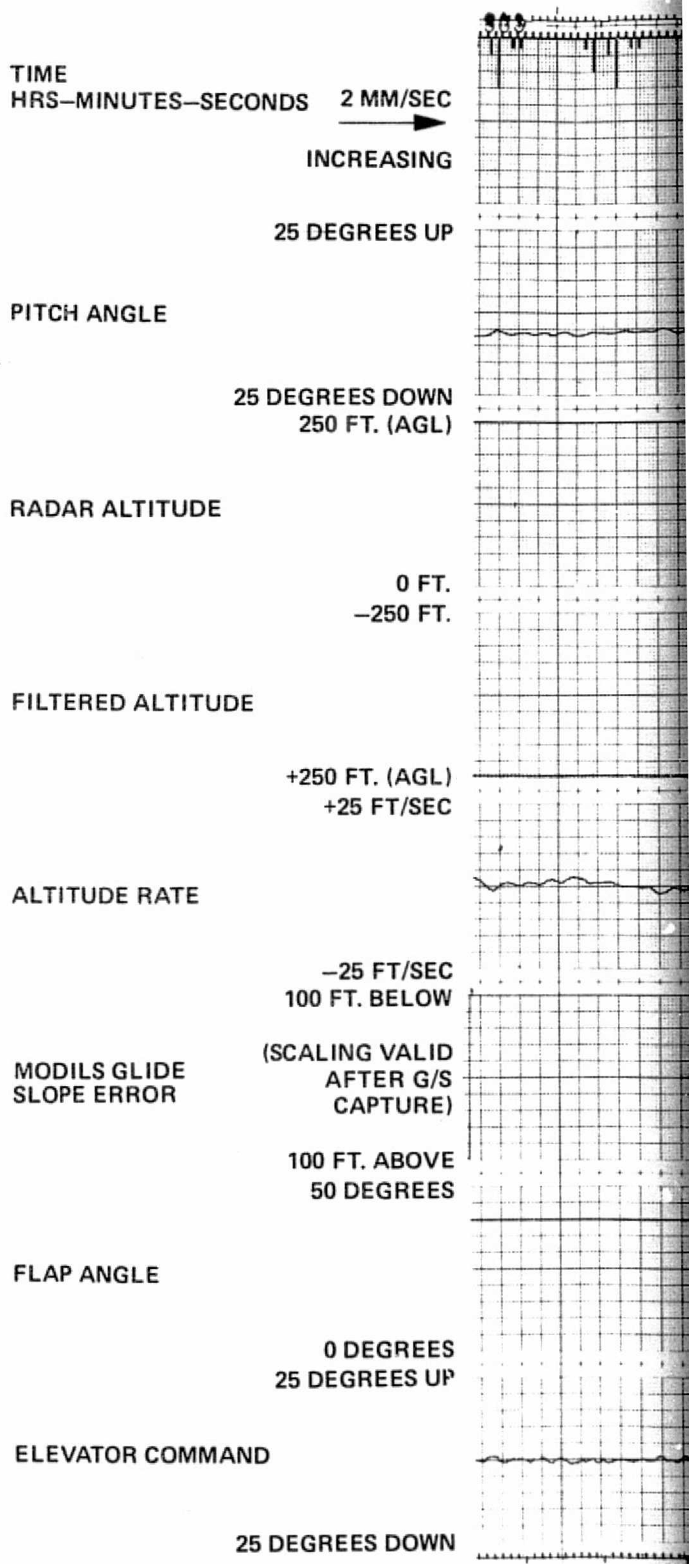
–5 PSI





FOLDOUT FRAME 2

Figure 4-25
Twin Otter Simulator Data,
Glideslope Capture/Track and Flare



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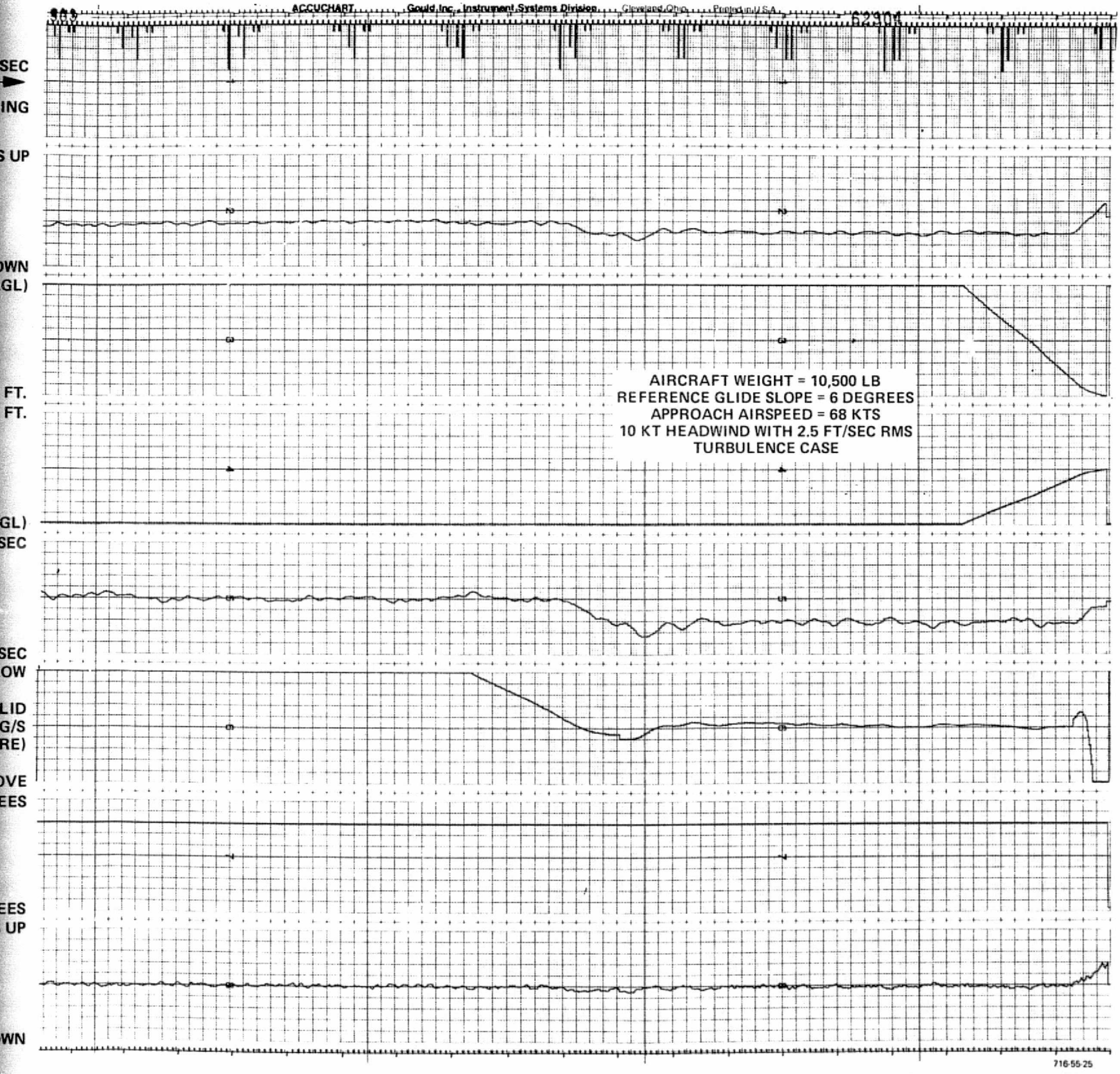
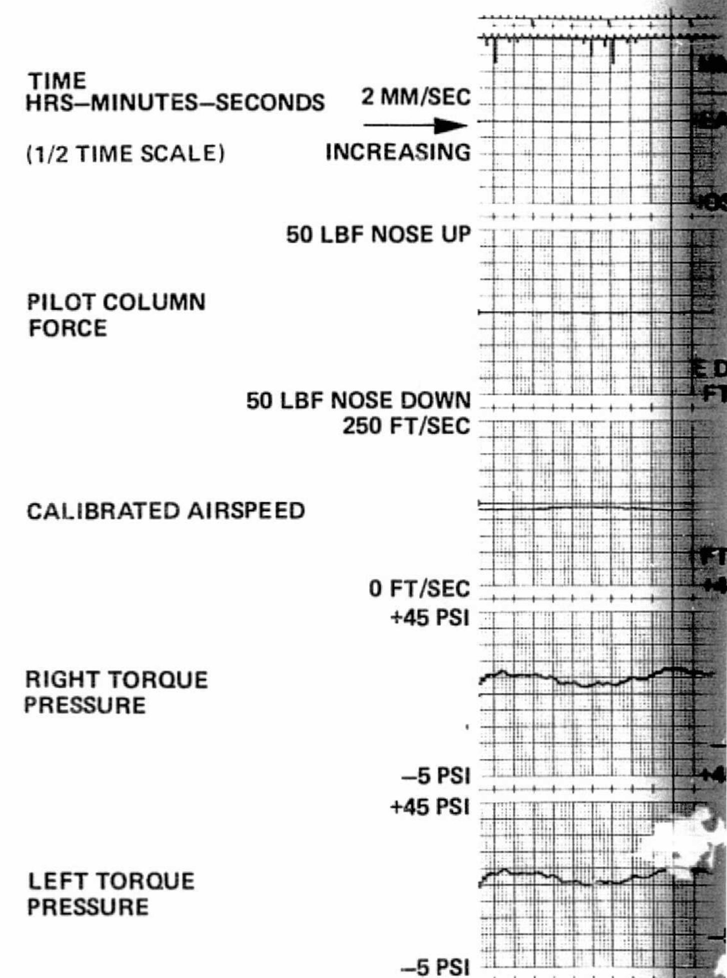


Figure 4-26
Twin Otter Simulator Data,
Glideslope Capture/Track and Flare

FOLDOUT FRAME 2



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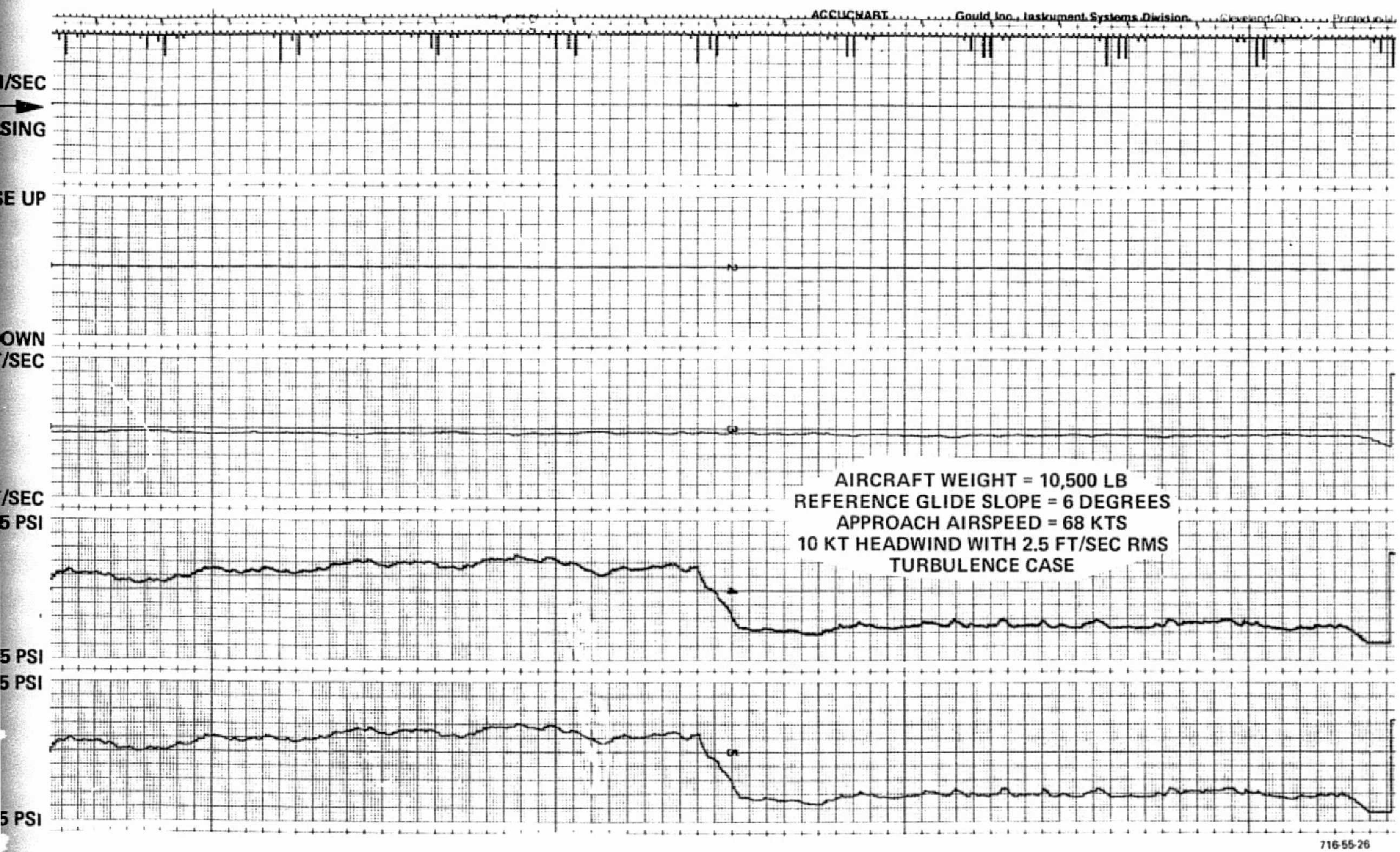
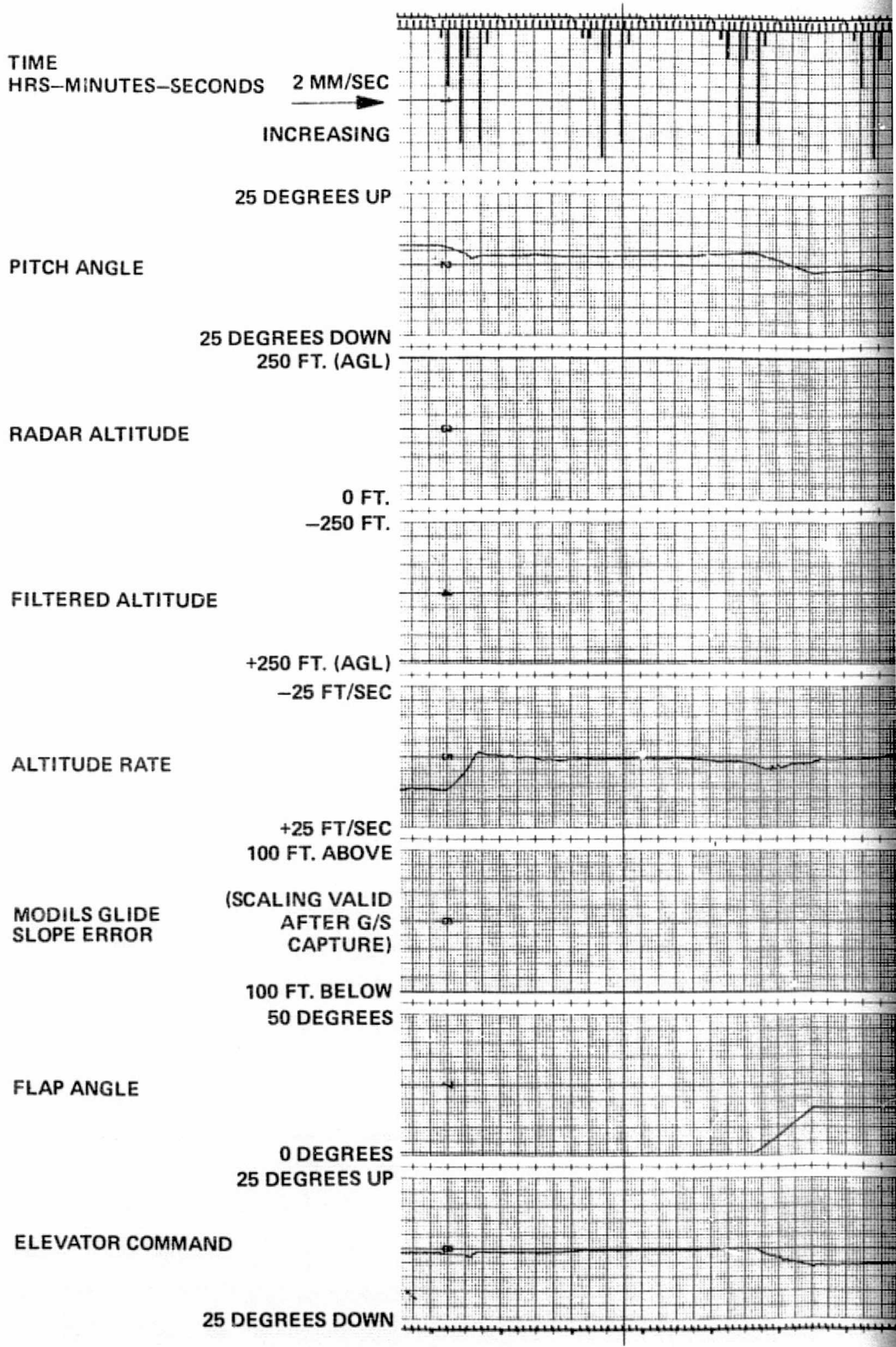


FOLDOUT FRAME 2

Figure 4-27
Twin Otter Simulator Data,
Glideslope Capture/Track and Flare



FOLDOUT FRAME

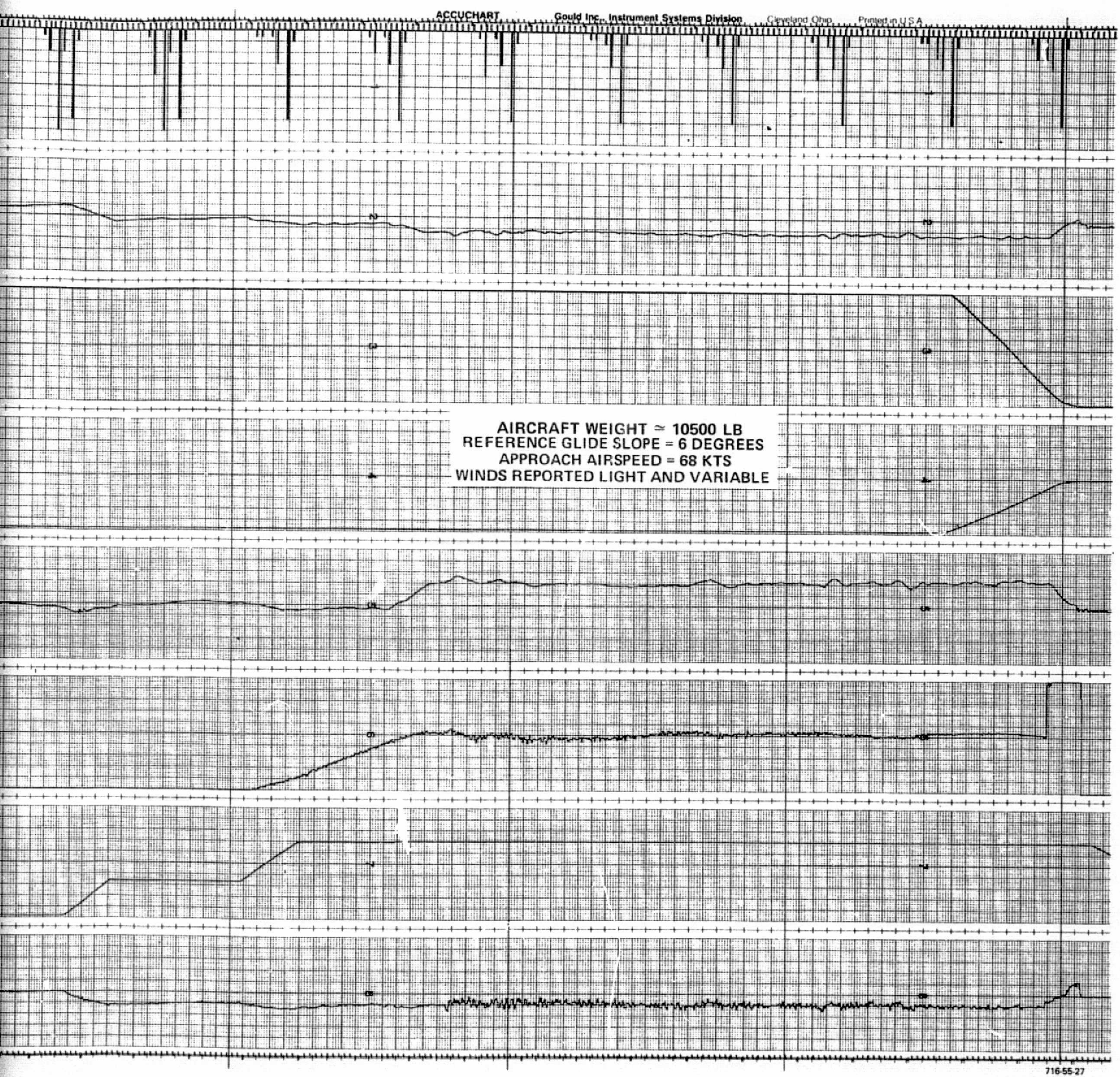
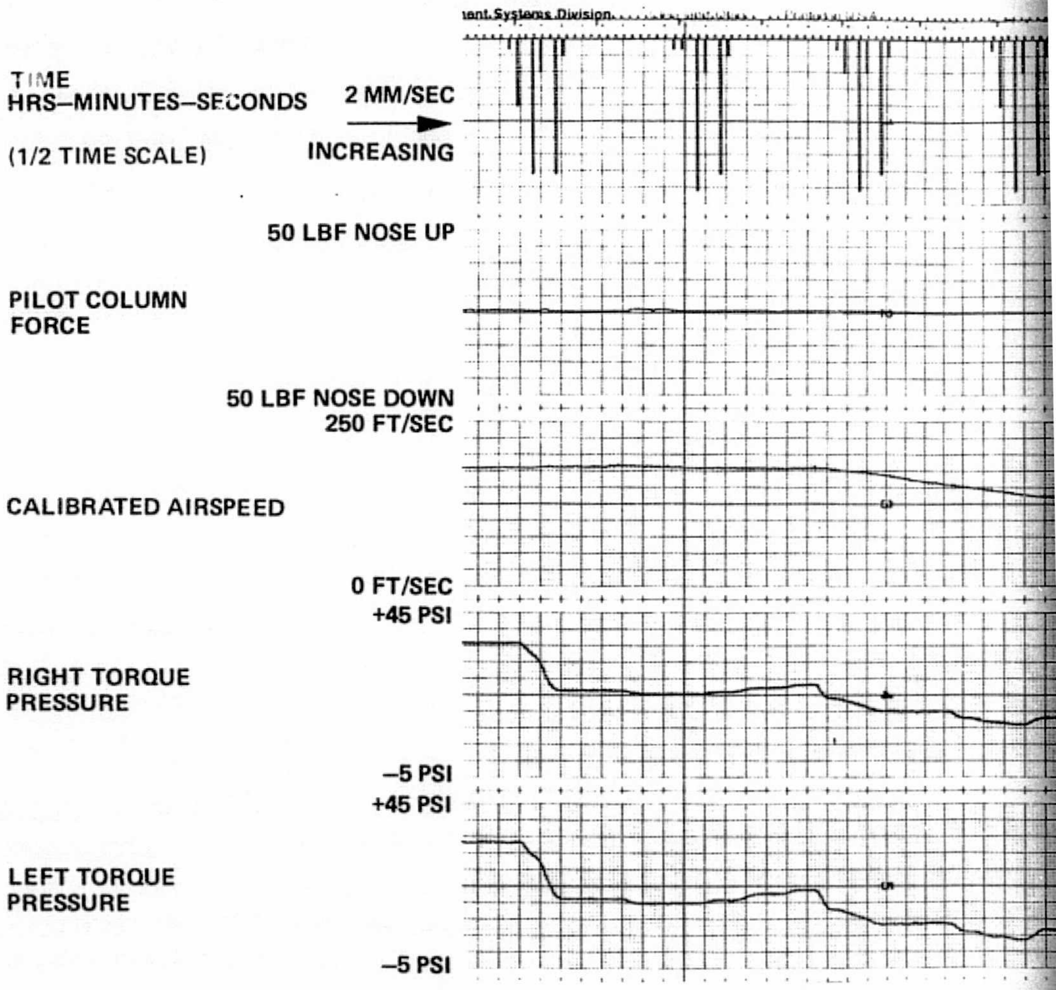


Figure 4-28
Twin Otter Flight Data,
Glideslope Capture/Track and Flare

FOLDOUT FRAME 2



FOLDOUT FRAME |

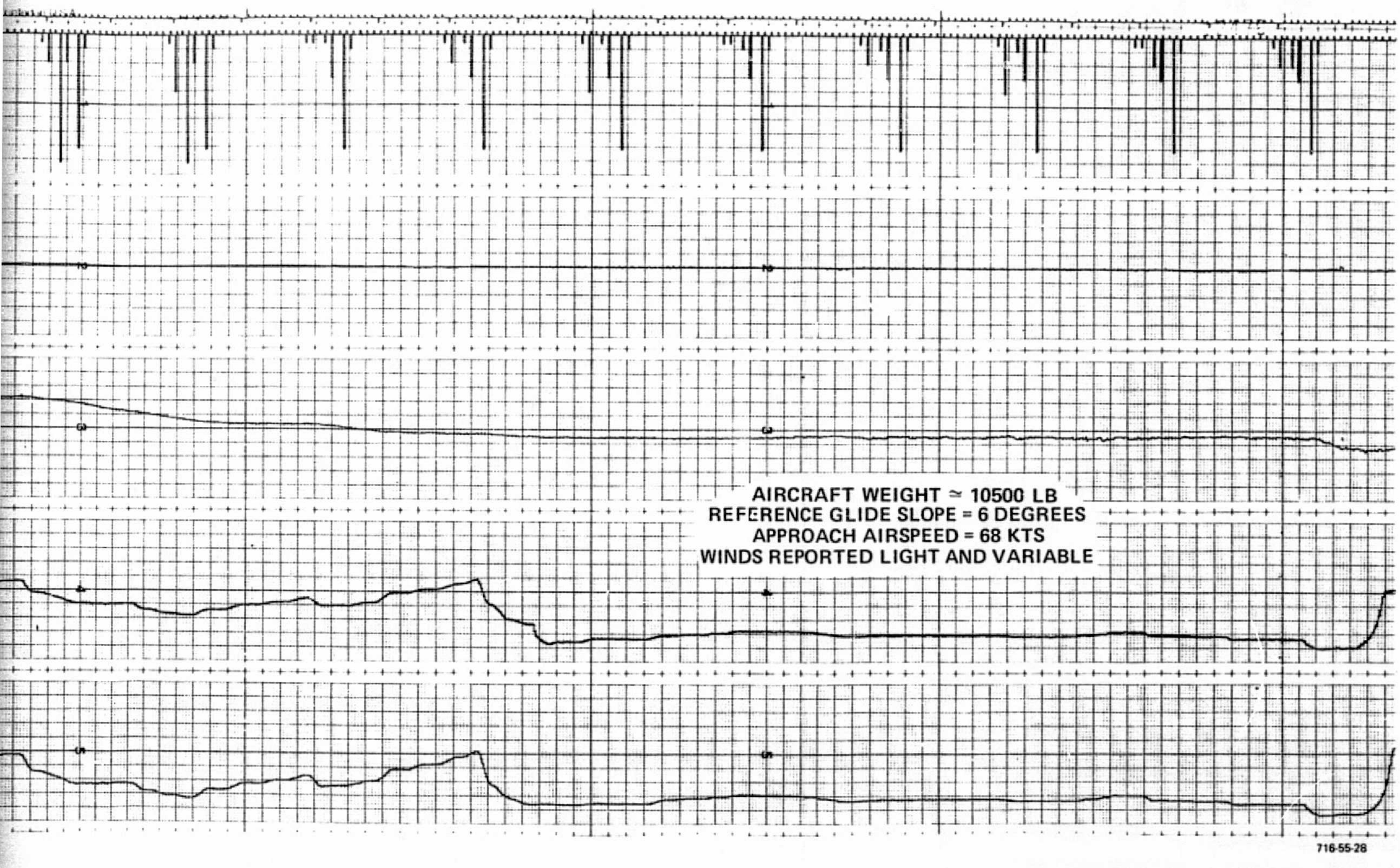


Figure 4-29
Twin Otter Flight Data,
Glideslope Capture/Track and Flare

FOLDOUT FRAME 2

The glideslope capture occurred around 18:30:25 where a sink rate of about 10 feet per second was established. The flare maneuver was initiated at about 40 feet and lasted about 5.5 seconds. The final touchdown sink rate and pitch attitude were 2 feet per second and +1.5 degrees, respectively.

SECTION V

OBSERVATONS AND RECOMENDATIONS

A. GENERAL COMMENTS

The STOLAND system is a versatile integrated digital avionics system that uses a central computer complex for all aircraft navigation, guidance, control and display functions. The system was designed so that it could be installed in any aircraft or simulator with almost no changes to the hardware and minor changes to the modular software. With installations in the CV340, Twin Otter and Augmentor Wing aircraft, this objective has been achieved and demonstrated.

The basic STOLAND equipment complement allows for flight experimentation in navigation, guidance controls and displays technology. Provision has been included to drive electromechanical and electrohydraulic actuation systems for as many as 11 primary and secondary flight controls. The various servos, and the general purpose electronic displays (EADI and MFD) as well as the electromechanical HSI are completely under software control. This allows rapid and flexible changes for experimentation purposes.

The system architecture allows use of existing state-of-the-art aircraft navigation sensors, cockpit instruments, control devices, etc, without requiring any interface design in that equipment. It also accommodates new types of sensors or subsystems with only minor modular hardware additions, and software changes sufficient to demonstrate only the functions associated with the added equipment. Provision is included to interface directly with external computer systems and thereby give them access to the basic STOLAND electronic displays and control actuation equipment.

The STOLAND system uses a unique validation technique that allows complete checkout of the system prior to flight testing. This technique employs a validation facility that provides duplication of the aircraft static and dynamic flight environment in regard to sensor measurements, data flow and control activity. The Airborne Hardware Simulator (AHS) interfaces with a simulation computer to provide this capability.

Software development capability is totally self-contained within the STOLAND airborne computer and associated peripheral equipment. The airborne system and validation facility have been designed for on-line as well as off-line use of the airborne computer in program editing, debugging, and assembly.

The STOLAND systems which have been installed in NASA STOL research aircraft have undergone full simulator validation and in-flight testing. The STOLAND system demonstration objectives which have been achieved are described below. Areas of difficulty which arose during the course of STOLAND software development and were resolved are discussed. Existing problem areas which were discovered in the flight testing phase of the system checkout will also be discussed. Finally, recommendations for work in the existing problem areas are presented.

B. STOLAND SYSTEM DEMONSTRATION OBJECTIVES

The STOLAND system functions may be divided into 14 general areas where performance was to be evaluated:

- Stabilization and control
- Navigation
- Basic autopilot, autothrottle and flight director control
- Basic navaid guidance modes
- Reference flight path modes
- 4D guidance
- Approach guidance
- Flare
- Decrab
- Go-Around

- Displays
- Operational logic and compatibility
- Safety monitoring and information displays
- Data acquisition and reduction

All of the above demonstration objectives for both the Twin Otter and Augmentor Wing systems were tested using the STOLAND Validation Facility at NASA/Ames where proper performance and operation were verified in the simulation environment. Flight testing of the STOLAND system was then conducted and all of the above objectives were demonstrated in flight with the exception of those problem areas defined in Paragraph D of this section. In many cases, the problems discovered in flight testing were in areas where the simulation knowledge of the aircraft was known to be less accurate, such as in flare where the ground effect was not well specified. In some cases, flight problems were not discovered in the simulator validation process because the test procedures were not subtle enough to identify them. However, the number of these problems was small when the total scope of the STOLAND system objectives is considered.

To add to the complexity of the STOLAND system design, functional areas such as 4D guidance and operational requirements were not well defined, and many modifications to these areas were made as the program developed, some even during the flight testing phase. As such, these areas may be considered to be experimental in nature.

C. RESOLVED AREAS OF DIFFICULTY

In this paragraph, areas where operational problems had to be resolved are discussed. Some of these problem areas were related to the unique Augmentor Wing aircraft control configuration which includes nozzles and augmentor flaps. Others represent problem areas which are characteristic of the control problems that are encountered when an attempt is made to control an aircraft in the STOL region of flight.

One of the major performance objectives of STOLAND was to achieve control of the vehicle in the STOL flight configuration. During the course of the design work to achieve this control the question of safe control in this configuration was raised. It was felt that the system could be designed to guarantee safe maneuver margins while controlling on the approach glideslope to touchdown. This concept was then modified to include safe maneuver margin control constraints in all regions of flight.

For the Twin Otter aircraft the accepted .69g maneuver margin minimum was adopted and the system was modified to limit the airspeed to which the system would control to values consistent with the .69g minimum. For the Augmentor Wing aircraft the minimum maneuver margin which would be acceptable as well as the means for achieving this minimum maneuver margin were not as easily determined. The augmented lift derived from the augmentor flaps and the nozzles affected the minimum maneuver margin concept. It was decided that, whenever the flaps were deployed more than 30 degrees, a minimum maneuver margin of .4g (computed from aerodynamic lift only) would be acceptable since additional vertical maneuvering capability was available via the augmentor lift devices. At all other times, the conventional .69g value would be used. Implementation of the minimum maneuver margin concept on the Augmentor Wing involved limiting airspeed and engine rpm (thrust) as a function of aircraft flight path angle, weight bank angle and flap angle. This was accomplished with interpolation within 3 dimensional tables of data stored in the computer memory. This, again, demonstrates the versatility of the digital computer in the system.

The initial STOLAND longitudinal control of the Augmentor Wing in the low speed STOL configuration (flaps and nozzles down) used the conventional aircraft method of controlling the flight path with elevator and speed with autothrottle. Later, development work on the Sperry simulation demonstrated that more effective control could be achieved using the autothrottle for flight path and the elevator for speed. This is not surprising because in the STOL configuration, a large percentage of the lift on the Augmentor Wing derives from the downward pointing hot thrust nozzles and from the cross

ducted engine bypass air flaps. This reversed method of control was incorporated in the airborne system and became known as the STOL Mode. The mode is introduced automatically when the flaps are lowered more than 45 degrees.

Another problem area which was unique to the Augmentor Wing aircraft was that of hysteresis in the throttle controls. A hysteresis zone equivalent to 2 to 3 degrees of throttle lever lost motion was generated somewhere in the aircraft throttle control linkages. The effect of the hysteresis on the throttle control loop, which was closed on a pseudo throttle position derived from throttle servo rate, was to greatly reduce the control bandwidth and therefore the performance of the system. It was determined that this last motion could not be removed without extensive throttle control linkage modifications. A change to the STOLAND throttle servo loop was therefore made to compensate for the adverse effects of the hysteresis. The pseudo throttle position loop, which was closed in the software, was replaced with a control loop closure on engine rpm which was available as an input to the computer. Because of the engine response lag in this rpm control loop, a lead function was generated in the software for compensation. This lead function also served the purpose of driving the throttle levers through the hysteresis zone rapidly for small rpm loop errors. The effect of this software modification was to effectively eliminate the inner loop control problem (at the expense of somewhat increased throttle lever activity).

Another major problem area which affected both the Twin Otter and Augmentor Wing versions of STOLAND was the existence of navigation data dropouts. In flight test, it was determined that the navigation data (mostly VOR and TACAN) would sometimes take large steps to incorrect values for short periods (10 to 20 seconds) without any loss of the corresponding valids. The navigation filters incorporated in the software were not, at the time, able to cope with these data dropouts and large guidance transients would result. The navigation program was modified to include data dropout protection. The dropout protection scheme compares the raw computed X and Y values to the filtered values of these quantities and the navigation reverts to a dead reckoning mode (using the last wind estimate) wherever there is not a reasonable agreement between the raw and filtered data. The reasonable comparison

level was set at a value (a function of range to station) of about 2 to 3 times the measured noise level of the raw data which was still well below the level of the data dropouts. This scheme has worked well in flight.

D. REMAINING PROBLEM AREAS

A few remaining problem areas were uncovered during the flight tests of the Twin Otter and Augmentor Wing STOLAND systems. While the causes of most of these problems have been studied and are known, solutions have generally not been implemented because of schedule and funding considerations. These problem areas will be described here. Recommendations are given in Paragraph E of this section. A significant problem area which was uncovered during Twin Otter flight testing is the occurrence of navigational errors after a typical STOL decelerating turning approach. Although it was not as obvious, the problem also existed with the Augmentor Wing system. The navigational errors resulted in poor localizer tracking until these errors were washed out in the navigation filter. However, because very short final approaches (1 to 2 miles) were being attempted, the filter errors would not have time to be completely washed out before touchdown.

These navigational errors are known to be generated by vertical gyro errors which occur when the vertical gyro slaves to a false vertical during the downwind deceleration before the turn onto final. During the turn onto final, the gyro error, which is originally in the pitch attitude measurement, transfers into the roll attitude measurement. This roll error causes the filtered Y estimate to be in error when the aircraft comes out of the turn onto the final segment. This gyro error has generated overshoots of up to 250 feet during localizer capture.

A problem was discovered late in the Twin Otter flight test which is unique to the Twin Otter aircraft. Perturbations in localizer tracking at and after glideslope capture have been observed. These perturbations have been demonstrated to be characteristic of a thrust mismatch that occurs between the right and left engines whenever thrust changes are required for speed control. An appreciable thrust reduction is required to hold speed as the glideslope is captured, and this is where the largest perturbation in localizer tracking occurs (up to 250 feet). A test in flight has shown that

a torque pressure mismatch of 4 to 5 psi will generate a yawing moment which will disturb the aircraft 250 feet from the localizer centerline. This problem was originally complicated by the effects of low frequency noise on the MODILS localizer data which was also disturbing the aircraft from the centerline. However, the MODILS noise problem was solved by gain scheduling the localizer track gains which resulted in reduced gains at ranges where the noise was a problem.

An Augmentor Wing glideslope track performance problem was discovered in the flight test. This problem was characterized by the existence of a fairly lightly damped mode with a period in the vicinity of 12 seconds. This mode would be excited by turbulence and result in fairly large excursions in flight path angle. However, the vertical deviation error would hardly ever exceed 20 feet. The mode was somewhat reproducible on the simulator in that it would occasionaly appear in runs where large values of turbulence were used. In flight the mode was much more visible and would easily be observed in relatively light turbulence. This lightly damped mode is known to be the result of high glideslope track gains coupled with the relatively low bandwidth throttle control of flight path. The high glideslope gains were found necessary in the simulator to give adequate control tightness in the presence of turbulence and wind shears.

A final problem area, again discovered in the flight tests, is that of flare control on both the Augmentor Wing and Twin Otter aircraft. In both cases, flare laws were developed and extensively tested under various conditions (turbulence, wind, weight variations, cg variations, etc) on the STOLAND validation facility at NASA/Ames. Performance on the simulator was good in each case. However, in flight results were always quite different from those obtained in the simulator. The Augmentor Wing in-flight flare demonstrated a tendency to rapidly arrest the rate of descent and result in a float situation which the closed loop law would then attempt to correct. The major characteristic of the Twin Otter in-flight flare was a tendency to be inconsistent. It was observed that, under what appeared to be identical flare entry conditions, the $(h, \dot{h})$ phase plane plot could vary largely with an almost identical pitch attitude rotation maneuver. One flare would give a light touchdown, the next would hardly arrest the rate of sink.

In general, the differences in performance between the simulator and in-flight flare results may be attributed to two factors. First, the area in which the simulation is probably the least accurate is flare dynamics. The ground effect is not well known on the Augmentor Wing and Twin Otter and on both simulations there was no observable ground effect when the aircraft was allowed to fly into the ground, undisturbed, following disconnect of the automatic controls immediately prior to the flare. For the Twin Otter, thrust characteristics (drag effects) in the low torque pressure range when the flare is performed are extrapolated and have not been measured. Secondly, a largely predictive command is used for the flare maneuver. This predictive command must be relatively precise because of the limited bandwidth available for tight closed-loop control of h and $\dot{h}$ during the flare. Therefore, the in-flight success of a simulator tuned flare law is closely tied to the accuracy of the simulation. This becomes even more critical in the STOL aircraft where the flare maneuver is large in terms of attitude change and rate of attitude change. The margin for error in the predictive maneuver becomes smaller.

E. RECOMMENDATIONS

The problem areas described in Paragraph D are not insurmountable and the causes are, for the most part, well understood. In some cases partial solutions have been implemented already. A discussion of these solutions as well as recommendations for work which should result in increased performance in these areas are presented here.

A solution for the navigational errors, the effects of which were more obvious in the Twin Otter STOLAND system, has been implemented in both STOLAND systems. Since the errors in Y and $\dot{Y}$ were being caused by the vertical gyro errors, it was decided to increase the MODILS navigation filter gains to make the filtered quantities more dependent on the navigation data and reduce the contributions of the inertial sensors. The filter time constants (range dependent) were reduced from 40 to 60 seconds to 10 to 15 seconds for MODILS. This had the effect, in the simulator with a simulated gyro roll error of 2 degrees, of reducing the localizer capture overshoot from 250 feet to 75 feet. However, this increase in performance was obtained

at the expense of increased MODILS noise effects on the filtered navigation quantities, especially on lateral rate, $\dot{Y}$. These effects were reduced by localizer gain scheduling with range as described in Paragraph D above.

With this solution the localizer capture performance for the short decelerating/descending approach is considered to be acceptable by the pilots. However, additional improvement in performance could be achieved if the gyro error were eliminated through the use of an INS system. This would allow the MODILS navigation filter gains to be set back to lower values which are better from a noise standpoint.

The Twin Otter localizer track perturbation problem due to engine-generated yawing moments has been handled with a pilot technique. The largest perturbation occurs after glideslope capture when the throttles have just been reduced to maintain airspeed on the descending glideslope. At this point the pilot balances the torque pressure readings on the right and left engines which may be 4 to 5 psi different. He also monitors the torque pressures during the approach to keep the torque pressures reasonably balanced as the autothrottle moves the throttle levers to control airspeed. This method has resulted in good localizer tracking performance. However, it requires the pilot to monitor the torque pressures where the intent was to have the system perform the approach and landing without any pilot assistance.

Two modifications could be made to the system to cope with the engine generated yawing moment problem. These modifications would use rudder control to essentially cancel the effects of the engine yawing moment. When the yawing moment occurs, resulting in a rapid change of heading, it quickly changes the aircraft velocity vector, which in turn causes a lateral position error to build up. The present system will compensate for this increasing lateral error as it builds up by banking the aircraft. However, an appreciable lateral error may develop before the effects of the bank will start to compensate for the error. Better compensation would result if the localizer bank command $[\emptyset_c = K_1 (Y + K_2 \dot{Y})]$ were crossfed directly into the rudder

control. This would allow the rudder to assist in maintaining the proper heading in the presence of the yawing moment and would reduce the lateral excursions. However, this would also miscoordinate the turns slightly. The miscoordination would not be objectionable since any banking done on the localizer approach would be less than 10 degrees.

One weakness of the bank command crossfeed to rudder method is that a lateral error must build up before any rudder is deflected to compensate for this error. The amount of lateral error which would occur for a given yawing moment would depend on the value of the crossfeed gain which would be limited for stability reasons. The most direct method of compensating for the yawing moment with the rudder would be to add a rudder predict term to the rudder control law. This term would be of the form:

$$\delta_R \text{ (PREDICT)} = K(\overline{q}) \; [N_1 T_1 - N_2 T_2]$$

where

$T_{1,2}$ = Engine torque pressure (psi), right and left

$\overline{q}$ = dynamic pressure

$N_{1,2}$ = Engine rpm, right and left

With this term properly adjusted in the rudder control law, the yawing moment could conceivably be cancelled as it develops and no heading change or lateral error would develop.

It is recommended that these methods of rudder compensation for the engine-generated yawing moment be evaluated first in the simulator and then in flight. For the simulator evaluation, the yawing moment effect of the engines should be simulated from either measured or estimated data.

The Augmentor Wing system has a glideslope track damping problem for which there appear to be two possible solutions. A first method of eliminating the lightly damped flight path angle mode would be to reduce the glideslope track gains. However, this would certainly reduce the path error tightness (about 20 feet) which is currently available. The second solution

would be to use the chokes to increase the bandwidth of the path control loop. These devices offer an almost instantaneous ±.1g vertical acceleration capability. They could be used for high frequency control with the throttles providing the long term corrections. With this method it is felt that the glideslope track performance could be greatly improved.

If the chokes are used to improve glideslope track performance, they will have to operate around a midrange bias point (about 31 percent closed). This changes the trim configuration for the approach and impacts the glideslope capture philosophy as well as the throttle and/or nozzle settings for trim. Either a higher power will have to be carried at the same nozzle setting, or the current power setting may be maintained by changing the static nozzle deployment value.

During the final portions of the Augmentor Wing flight test, attempts were made with moderate success to rework the flare law to eliminate the performance problems discovered in flight. A closed loop (h, $\dot{h}$) term was added to the throttle flare law to compensate for the floating tendency observed in flight. However, the logic (safety considerations) on this throttle closed loop term usually prevents the throttles from retarding until after the float situation has been established.

It became apparent after the Augmentor Wing flare flight testing that, even though the pitch attitude closed loop control gain on h and $\dot{h}$ has been increased to the limit of stability, the pitch control bandwidth is marginal for good flare performance in off-nominal conditions. The predictive pitch and throttle flare terms were adjusted for optimal operation on the simulator. The correctness of these terms is critical to the success of the flare. However, in flight they appear to add to the pitch closed loop to generate the floating situation.

Fairly early in the flare law design the test pilot requested that the flare initiate point be made as high as possible to give him a better chance to monitor the flare maneuver. This resulted in a flare law that does a relatively gentle maneuver and is inherently more susceptible to increased touchdown dispersions. If the flare law were revised to reduce the flare

initate altitude, this would cause the system to perform a flare which is closer to the way the pilots flare the airplane. If this is not objectionable to the pilots, it would have the benefit of reducing the touchdown dispersions.

It is recommended that an attempt be made to determine the aircraft characteristics better in the area of flare. This should amount to measuring the ground effect and incorporating this data into the simulation. If this could be done with reasonable accuracy, it would greatly simplify the task of improving the flare performance since meaningful adjustments could be made on the simulator. However, even with a good simulation, some in-flight adjustment of the flare law will probably be required.

A more successful Augmentor Wing flare law which would handle off-nominal cases better could be developed if a higher bandwidth control were used closed loop on h and $\dot{h}$. In the augmentor lift configuration (flaps down, nozzles deployed) the throttles are very effective for flight path control (they are currently used in this fashion for glide slope control). However, engine dynamics limit the bandwidth of any outer loop closed on throttles and it is questionable whether throttles could be used effectively during the flare for path control. The chokes, on the other hand, could provide a limited authority high bandwidth path control during the flare maneuver. The chokes have an almost instantaneous ±.1g vertical acceleration capability. The .1g value is on the order of the maximum acceleration required to perform the flare and it is obvious that the flare maneuver could not be accomplished with the chokes only. However, a pitch attitude rotation is mandatory during the flare maneuver to ensure a nose-up attitude at touchdown. This pitch rotation provides most of the required vertical acceleration (as well as the airspeed bleed off) to accomplish the flare maneuver. It therefore seems that a flare law designed around a predictive pitch rotation maneuver with the chokes providing high bandwidth closed loop path control would have a good chance of success. The throttles could be used in conjunction with the chokes in a predictive fashion or for long term (low bandwidth) closed loop path control during flare.

It should be noted that, if the chokes are to be used for control during the flare maneuver, they will have to be at a midrange biased position (about 31 percent closed) at flare initiate to guarantee the full $\pm .1g$ capability. This would require a revision of the presently used power and/or nozzle settings for the approach since the biased chokes would change the trim point. Also, the safety aspects (hardover effects) of using the chokes for the flare maneuver would have to be investigated.

It is unfortunate that although hardware was added to STOLAND late in the program to provide control of the chokes, the scope of the contract did not allow for redevelopment of a flare law using these devices.

The Twin Otter flare law has demonstrated a certain amount of inconsistency in flight. Again, this flare law performs well in the simulator, but gives different results in flight. In this case, the recommended procedure for solving this flare performance problem is straightforward. Additional data on aircraft characteristics in flare should be gathered. An attempt should be made to measure the ground effect. Also, the engine model should be made more accurate in the low torque pressure range. The currently extrapolated values for thrust in this range should be verified. These efforts should be made in an attempt to resolve the differences between simulator and in-flight performance. If these differences can be resolved, i.e., if the flight performance can be repeated in the simulator, the task of eliminating the current problem will be greatly simplified.

The current Twin Otter closed loop pitch flare control gain has been increased to the limits of stability. At present, there are no control devices available which would provide high bandwidth path control to assist the pitch loop. However, spoiler surfaces will soon be installed in the Twin Otter aircraft and these lift/drag devices could be considered for use in the flareout maneuvers much as the chokes would be used for the Augmentor Wing. However, at present, a reasonable procedure for improving flare performance would appear to be to attempt to identify the factor or factors that are causing the inconsistent performance and modify the predictive terms in the flare law to compensate for these factors. All checkout and verification of any modifications will have to be performed in flight (keyboard gains may be used) since the simulator does not currently reproduce the problems seen in flight.

SECTION VI

LIST OF REFERENCES

1. Augmentor Wing STOLAND System Operation and Maintenance Manual, Sperry Pub No. 71-0873-00-00.

2. Twin Otter STOLAND System Operation and Maintenance Manual, Sperry Pub No. 71-0909-00-00.

3. STOLAND Program Documents:

Report No.	Title
5440-0222-P01	Stability Augmentation System (T.O.)
5440-0222-P101	Stability Augmentation System (A.W.)
5440-0222-P02	Autopilot and Flight Director Modes, (T.O.)
5440-0222-P102	Autopilot and Flight Director Modes, (A.W.)
5440-0222-P03	I/O Program
5440-0222-P04	HSI Program
5440-0222-P05	EADI Program
5440-0222-P06	STOLAND 3D/4D Guidance (T.O.)
5440-0222-P106	STOLAND 3D/4D Guidance (A.W.)
5440-0222-P07	Keyboard Program
5440-0222-P08	MFD Program
5440-0222-P09	Mode Select Panel Program
5440-0222-P10	Navigation Program
5440-0222-P11	Air Data Program
5440-0222-P12	Monitor and Diagnostics Program
5440-0222-P13	Preflight Test Program (T.O.)
5440-0222-P113	Preflight Test Program (A.W.)
5440-0222-P14	Master Executive and Timing
5440-0222-P15	Magnetic Tape and DDAS
5440-0222-P16	Speed Control Program (T.O.)
5440-0222-P116	Speed Control Program (A.W.)

4. STOLAND Data Adapter Performance Specification, Revision F, Pub No. 71-0568-00-01

5. D.W. Smith, F. Newman, D.M. Watson and G.H. Hardy: A Flight Investigation of a Terminal Area Navigation and Guidance Concept for STOL Aircraft. NASA TMX-62,375, July 1974